SIDDARTHA INSTITUTE OF SCIENCE AND TECHNOLOGY
(Approved by A.I.C.T.E., New Delhi & affiliated to J.N.T.U. Anantapur)
(Accredited by NAAC with 'A' Grade)
(An ISO 9001:2008 certified institute)
Siddharth nagar, Narayanavanam road, Puttur- 517583
Chittoor Dist., AP., INDIA

(20EC0433) OPTICAL FIBRE COMMUNICATION

UNIT-1
Introduction to optical fibers

SYLLABUS

UNIT-I

Introduction: The general Optical Communication System, Advantages & disadvantages of Optical fiber communication, Ray Theory transmission: Optical Fiber Structure, Total internal reflection, Angle of incidence, Refractive Index, Numerical Aperture, Skew Rays, Single mode & multimode fibers, Step index & graded index fibers,

Transmission Characteristics of Optical Fibers: Attenuation, Absorption losses, scattering losses, Bending Losses, Core and Cladding losses, Signal Distortion in Optical Wave Guides-Information Capacity determination, Group Delay, Intermodal dispersion.

UNIT-II

Fiber Optical Sources and Coupling: Direct and indirect Band gap materials, LED structures, Light source materials, Quantum efficiency and LED power, Modulation of a LED, lasers Diodes-Modes and Threshold condition, Rate equations, External Quantum efficiency, Resonant frequencies, Temperature effects.

SYLLABUS

UNIT-III

Fiber Optical Receivers: PIN and APD diodes, Photo detector noise, SNR, Detector Response time, Avalanche Multiplication Noise, Comparison of Photo detectors. Fundamental Receiver Operation, pre-amplifiers, Error Sources, Receiver Configuration

UNIT- IV

Optical Fiber System Design & Technology: System specification, Point-to- links, link power budget, Rise Time Budget, Bandwidth Budget, Power Budget (Adaptors, Attenuators and its effects must be explained) and Receiver Sensitivity, Link Budget calculations, Optical Multiplexing & Demultiplexing techniques, Optical Amplifiers and its Applications.

UNIT- V

Optical Networks: Basic networks, Broadcast-and-select WDM networks, Wavelength-routed networks, Performance of WDM+EDFA systems, Optical CDMA, Ultra high capacity networks.

Course objectives

The objectives of this course:

1. To understand Optical Fiber Communications.

2. To understand the Ray Theory, single& amplitude; multimode fibers, fiber materials,

losses, dispersion in OFC.

3. To understand the connectors, splices, couplers, LASER, LED sources.

Course outcomes

On successful completion of this course, the student will be able to

1. Learn the basic elements of optical fiber transmission link, fiber modes configurations and structures.

2. Understand the different kind of losses, signal distortion in optical wave guides and other signal degradation factors.

3. Learn the various optical source materials and optical receivers such as LED structures,

quantum efficiency, Laser diodes, PIN, APD diodes, noise performance in photo detector,

receiver operation and configuration.

4. Analyze the use of analog and digital links such as the various criteria like power loss

wavelength to be considered for point-to-point link in digital link system.

5. Learn the fiber optical network components, variety of networking aspects, and operational principles WDM.

6. Analyze the different techniques to improve the capacity of the system.

Evolution of fiber optic system

First generation

- Uses GaAs semiconductor laser
- Operating region was near 0.8 μm.
- Bit rate : 45 Mb/s
- Repeater spacing : 10 km

Second generation

- Bit rate: 100 Mb/s to 1.7 Gb/s
- Repeater spacing: 50 km
- Operation wavelength: 1.3 μm
- Semiconductor: InGaAsP

Continued.....

Third generation

- Bit rate : 10 Gb/s
- Repeater spacing: 100 km
- Operating wavelength: 1.55 μm

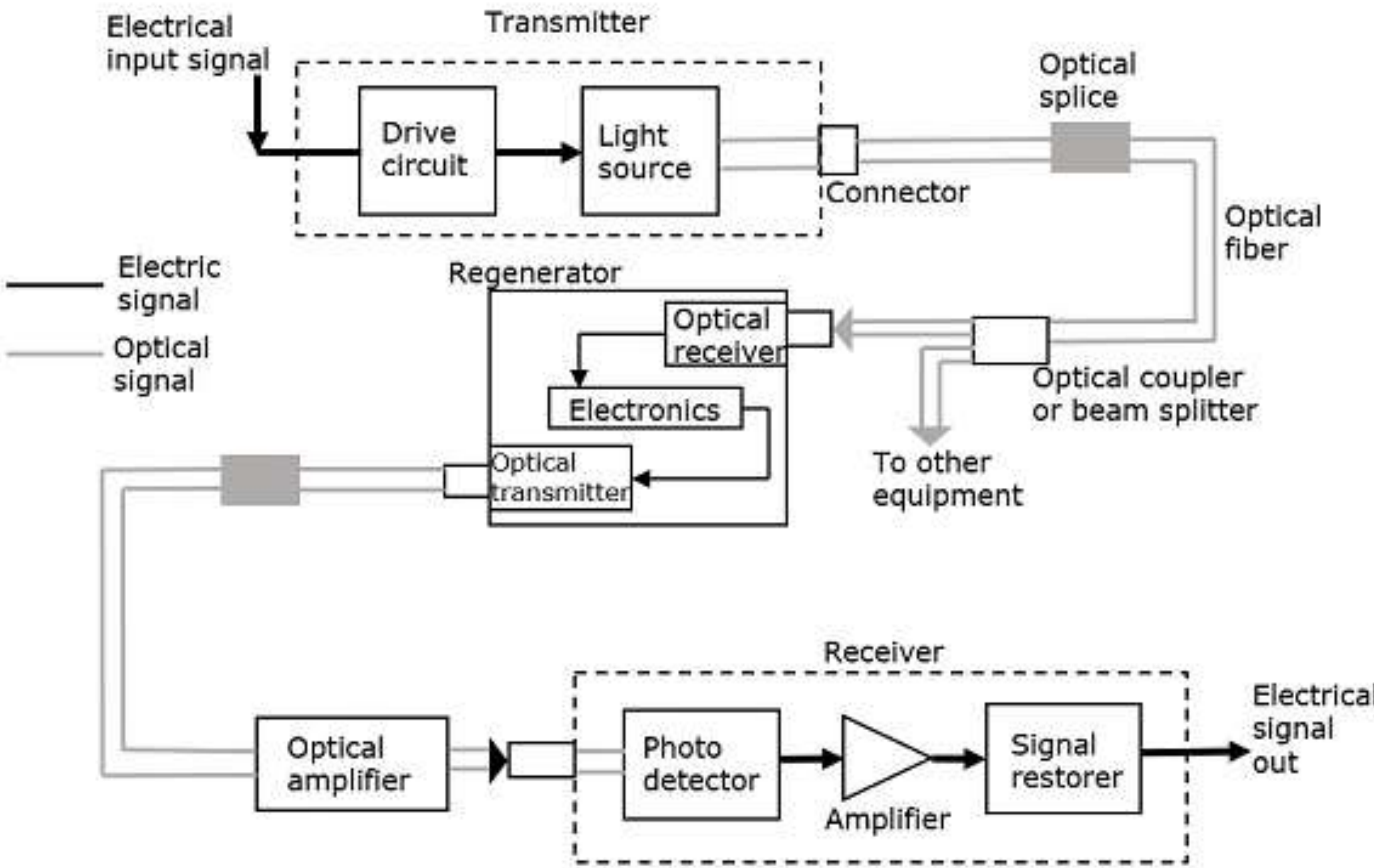
Fourth generation

- Fourth generation uses WDM technique
- Bit rate: 10 Tb/s
- Repeater spacing: > 10,000 km
- Operating wavelength: 1.45 to 1.62 μm

Fifth generation

- Uses Roman amplification technique and optical solitons
- Bit rate: 40 - 160 Gb/s

Elements of an Optical Fiber Transmission link



Advantages of Optical Fibre

- Thinner
- Less Expensive
- Higher Carrying Capacity
- Less Signal Degradation& Digital Signals
- Light Signals
- Non-Flammable
- Light Weight

Advantages of fiber optics

- Much Higher Bandwidth (Gbps) - Thousands of channels can be multiplexed together over one strand of fiber
- Immunity to Noise - Immune to electromagnetic interference (EMI).
- Safety - Doesn’t transmit electrical signals, making it safe in environments like a gas pipeline.
- High Security - Impossible to “tap into.”

Advantages of fiber optics

- Less Loss - Repeaters can be spaced 75 miles apart (fibers can be made to have only 0.2 dB/km of attenuation)
- Reliability - More resilient than copper in extreme environmental conditions.
- Size - Lighter and more compact than copper.
- Flexibility - Unlike impure, brittle glass, fiber is physically very flexible.

Fiber Optic Advantages

- greater capacity (bandwidth up to 2 Gbps, or more)
- smaller size and lighter weight
- lower attenuation
- immunity to environmental interference
- highly secure due to tap difficulty and lack of signal radiation

Disadvantages of fiber optics

- Disadvantages include the cost of interfacing equipment necessary to convert electrical signals to optical signals. (optical transmitters, receivers) Splicing fiber optic cable is also more difficult.

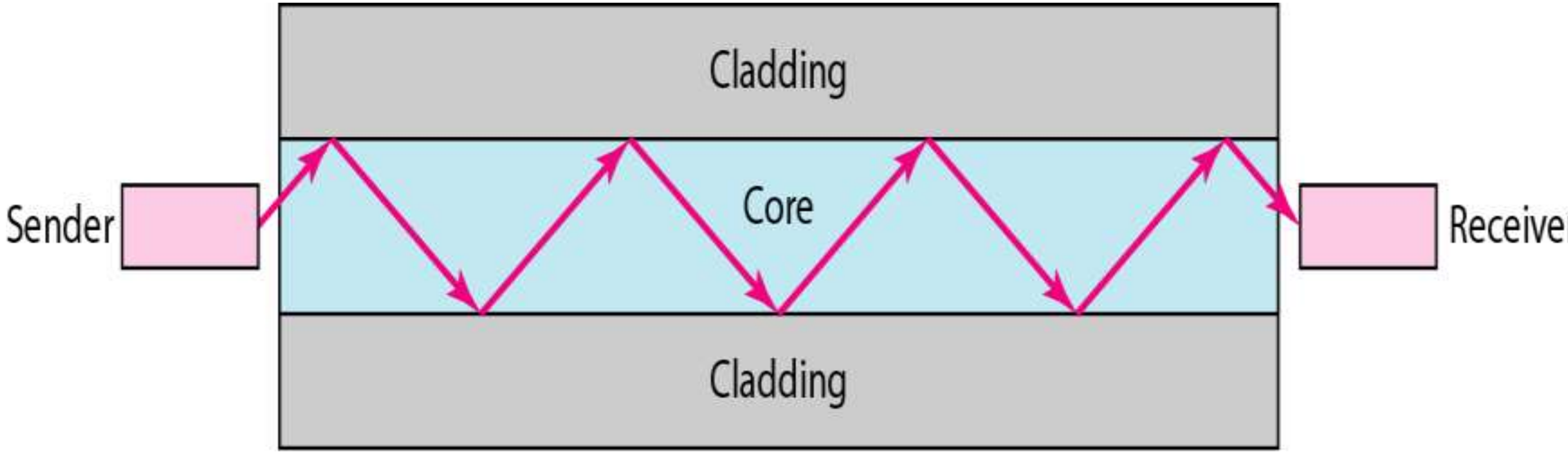
Areas of Application

- Telecommunications
- Local Area Networks
- Cable TV
- CCTV
- Optical Fiber Sensors

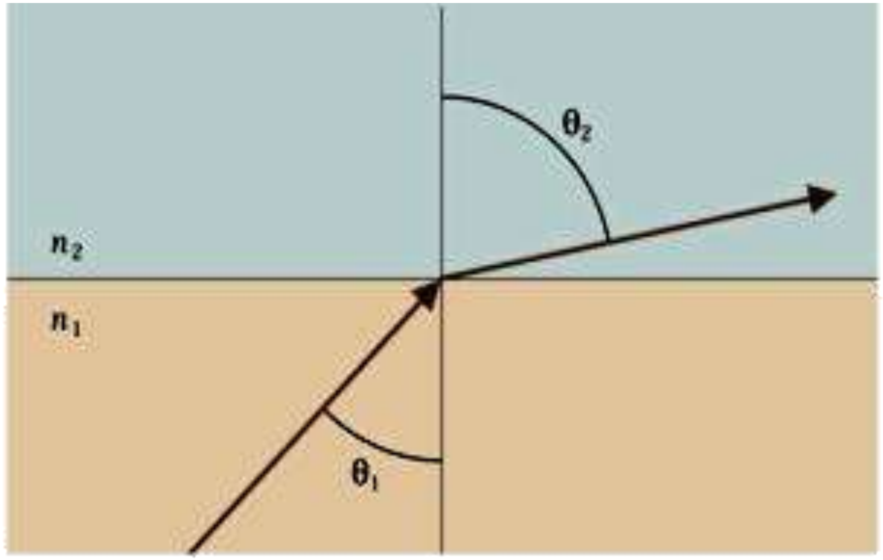
RAY OPTICS

Refraction and Total Internal Reflection

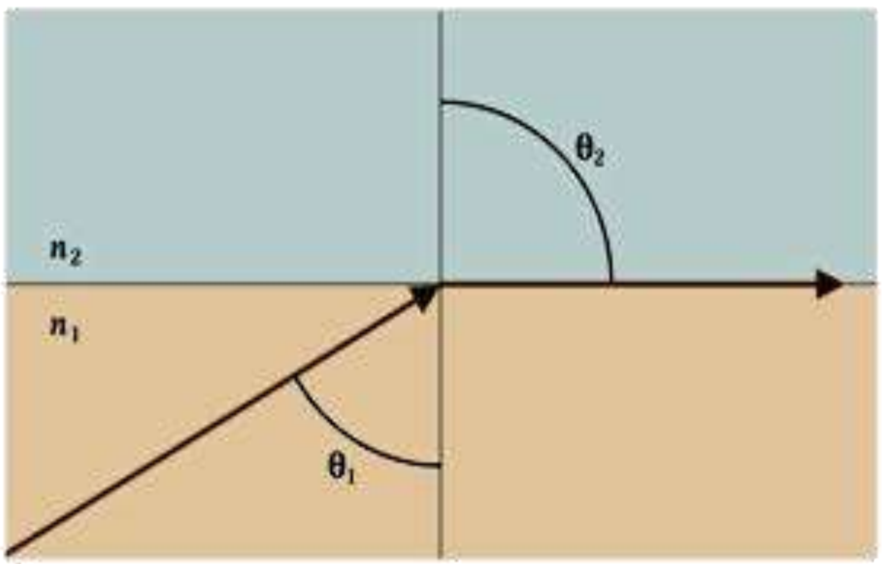
- Optical fibers work on the principle of **total internal reflection**
- The **angle of refraction** at the interface between two media is governed by **Snell's law:**



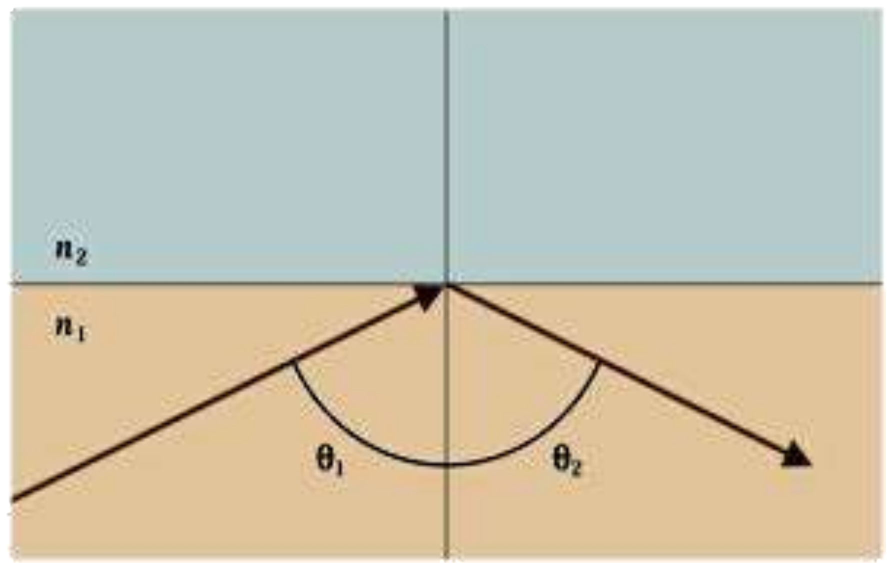
$$n_1 \sin \varphi_1 = n_2 \sin \varphi_2$$



(a) Angle of incidence less than critical angle



ngle of incidence equal to critical angle

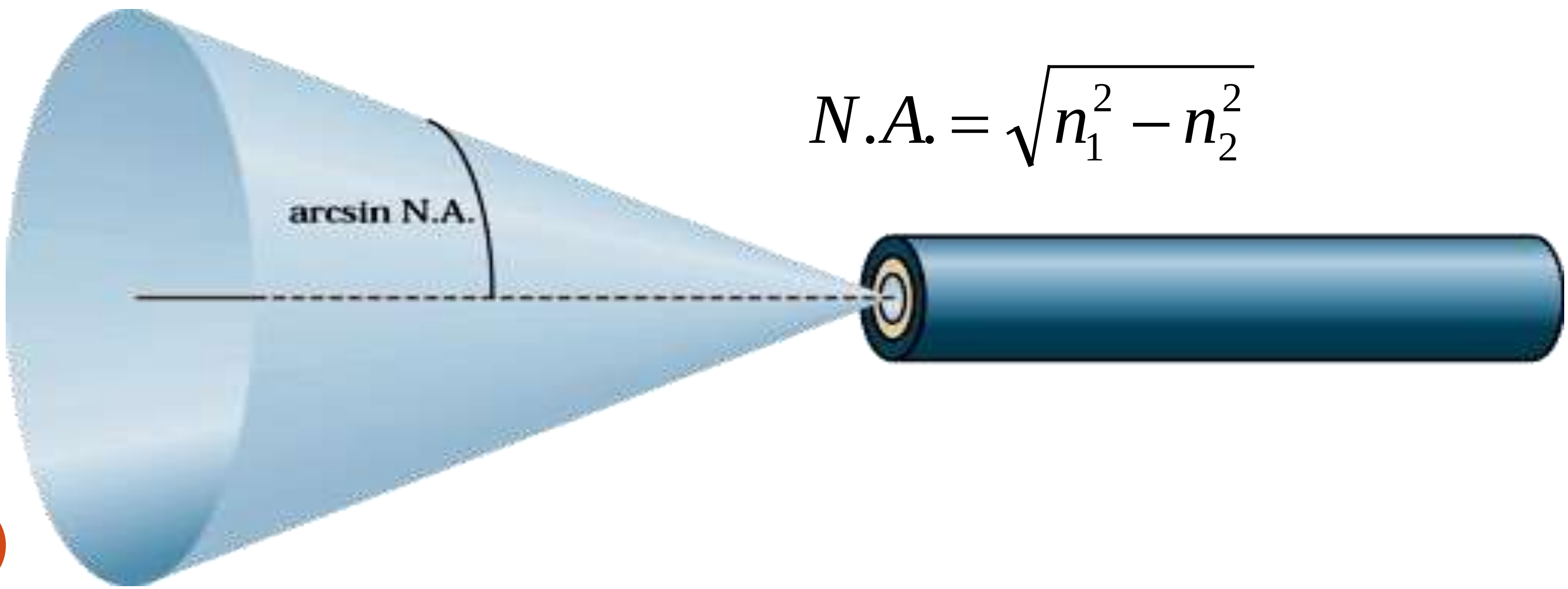


(c) Angle of incidence greater than critical angle

Numerical Aperture

- Light **gathering and acceptance** capability of fiber .
- The **angle of acceptance** is twice that given by the numerical aperture

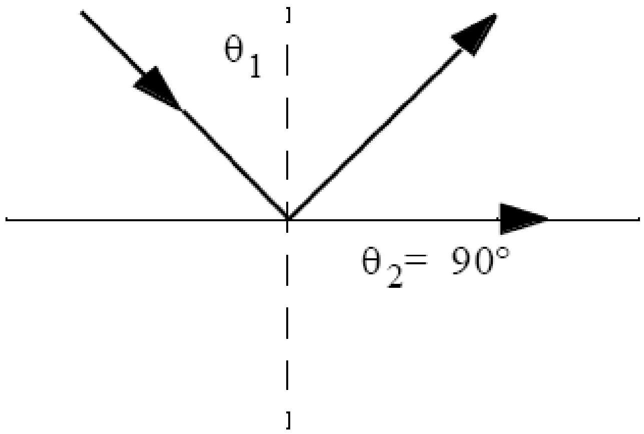
$$N.A. = \sqrt{n_1^2 - n_2^2}$$



Snell's Law

Total Reflection

If $n_1 > n_2$, then we can have

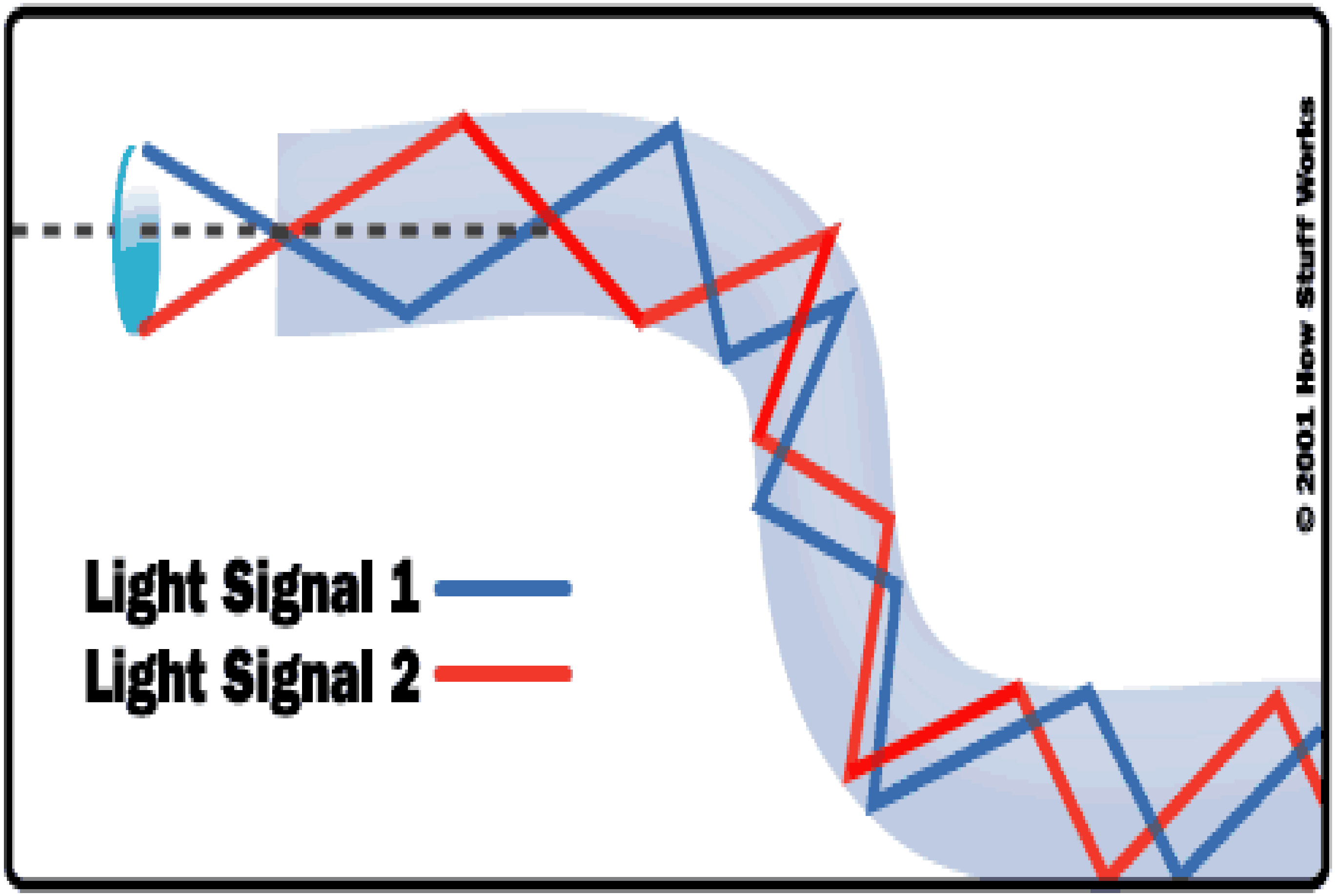


$$\theta_2 = 90°$$

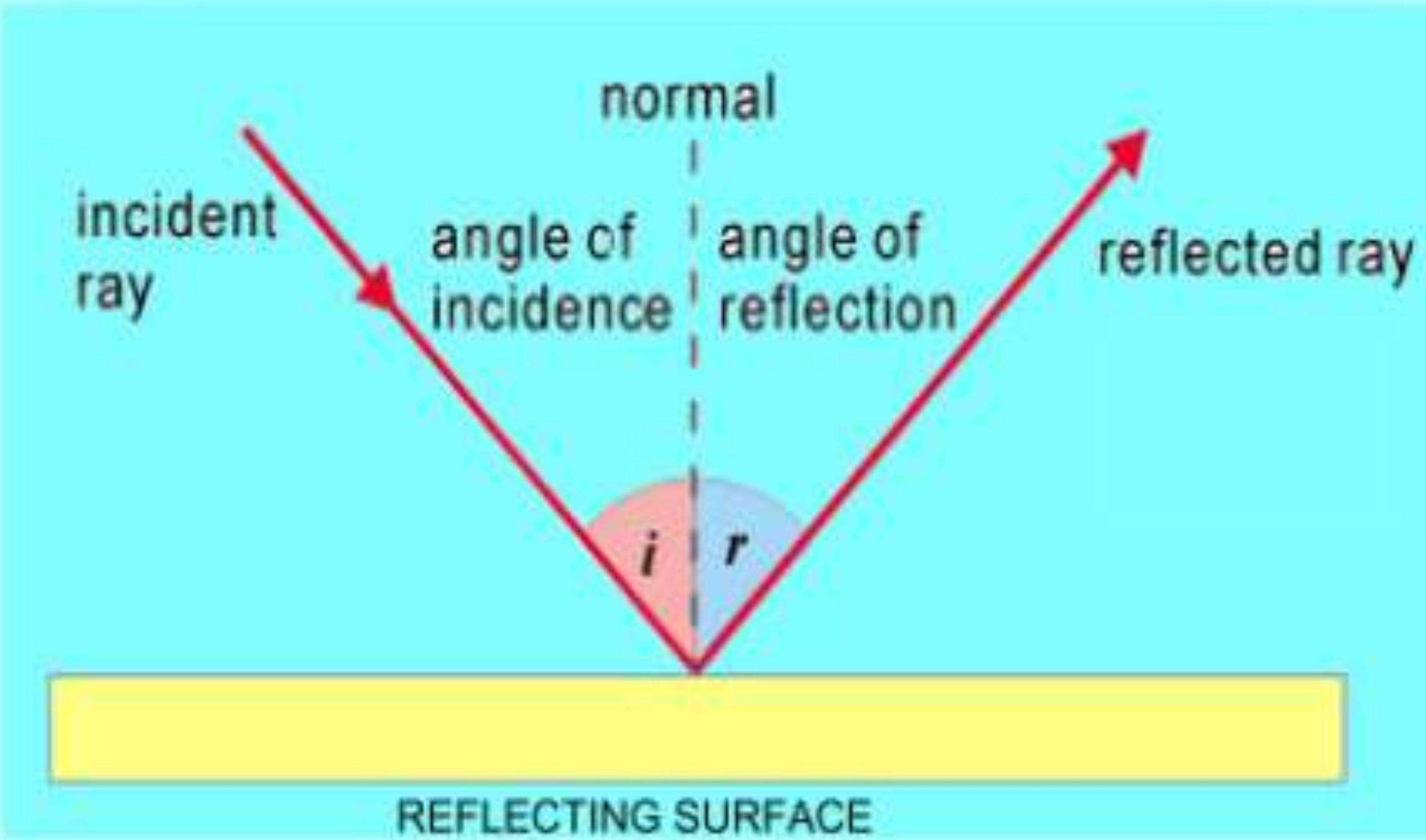
$$\sin\theta_c = \frac{n_2}{n_1}$$

$$\theta_c = \sin^{-1}(n_2/n_1)$$

Total Internal Reflection in Fiber



ANGLE OF INCIDENCE&ANGLE OF REFLECTION



REFRACTIVE INDEX

- Refractive index is denoted by 'n'

Refractive index(n)=velocity of light in first substance/velocity of light in second substance

Optical Fiber

- An optical fiber is cylindrical transparent waveguide that conveys electromagnetic waves at Optical frequency.

  It consists of

- **Core :**

  Carries light

  - Made up of glass
  - Refractive Index n1

- **Cladding :**

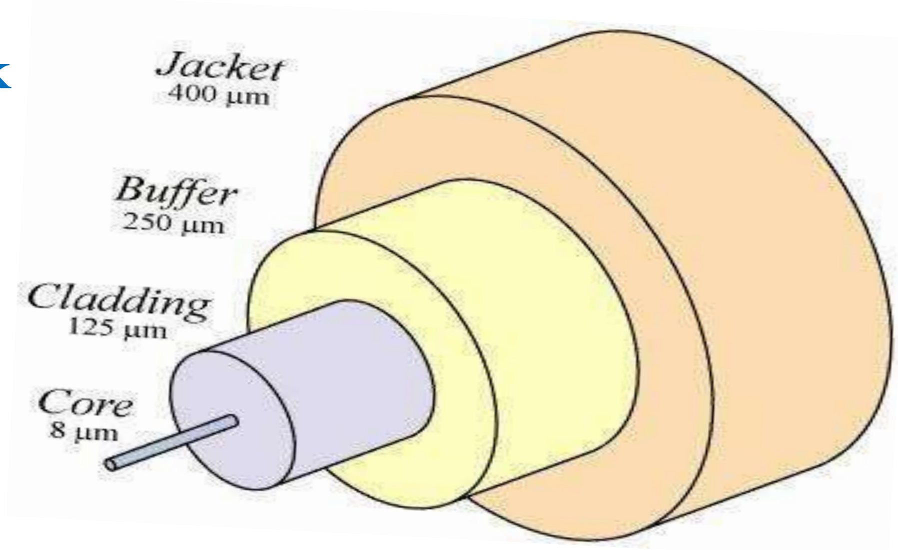
  Surrounds the core and refractive index is n2

  - Avoids scattering loss
  - Provide mechanical strength

- The **index of refraction** of the cladding is less than that of the core, causing rays of light leaving the core to be refracted back into the core

  n1>n2

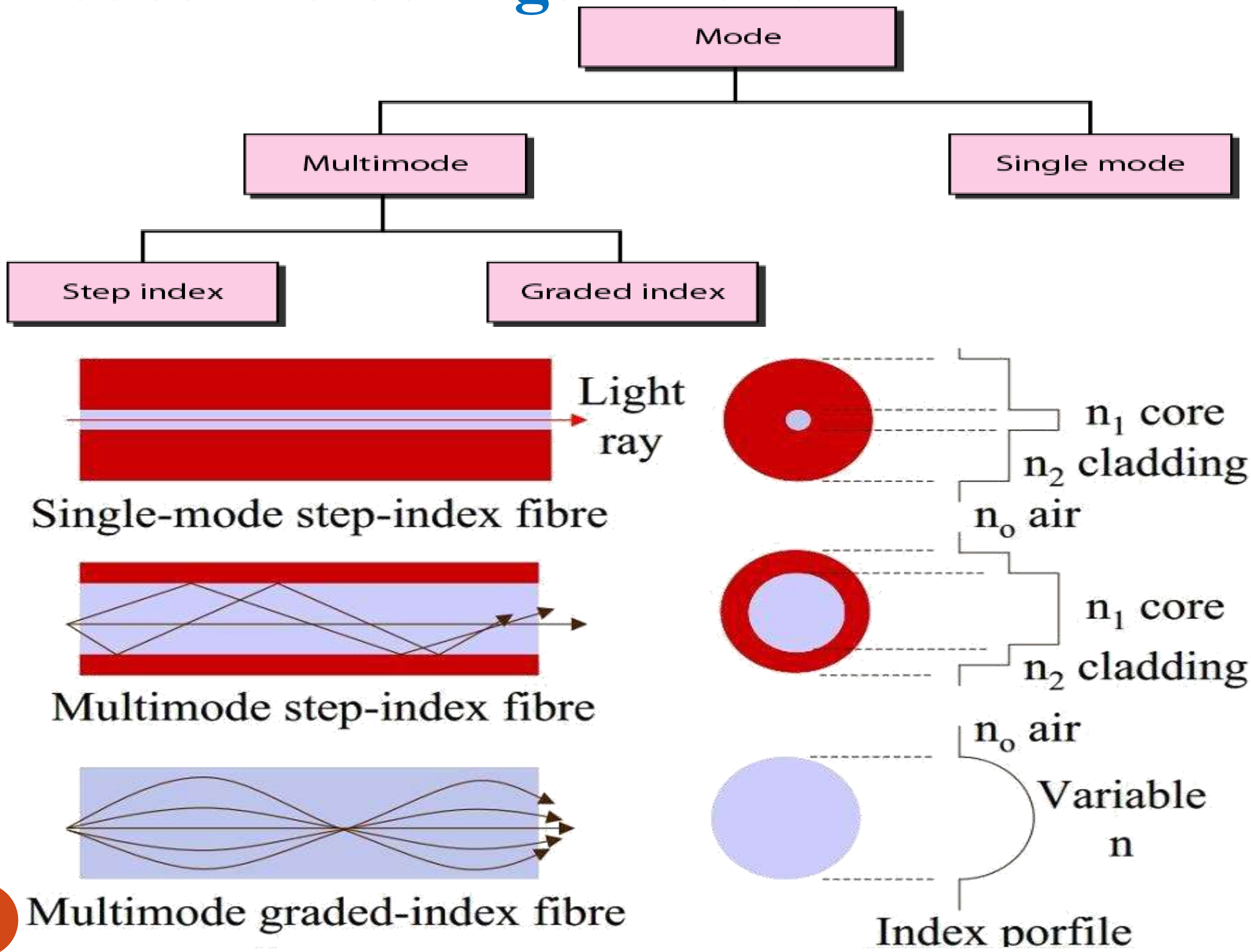
- **A light-emitting diode (LED) or laser diode (LD)** can be used for the source
- **Jacket:**
- **Advantages** of optical fiber include:
  - Greater bandwidth than copper
  - Lower loss
  - Immunity to **crosstalk**
  - No electrical hazard



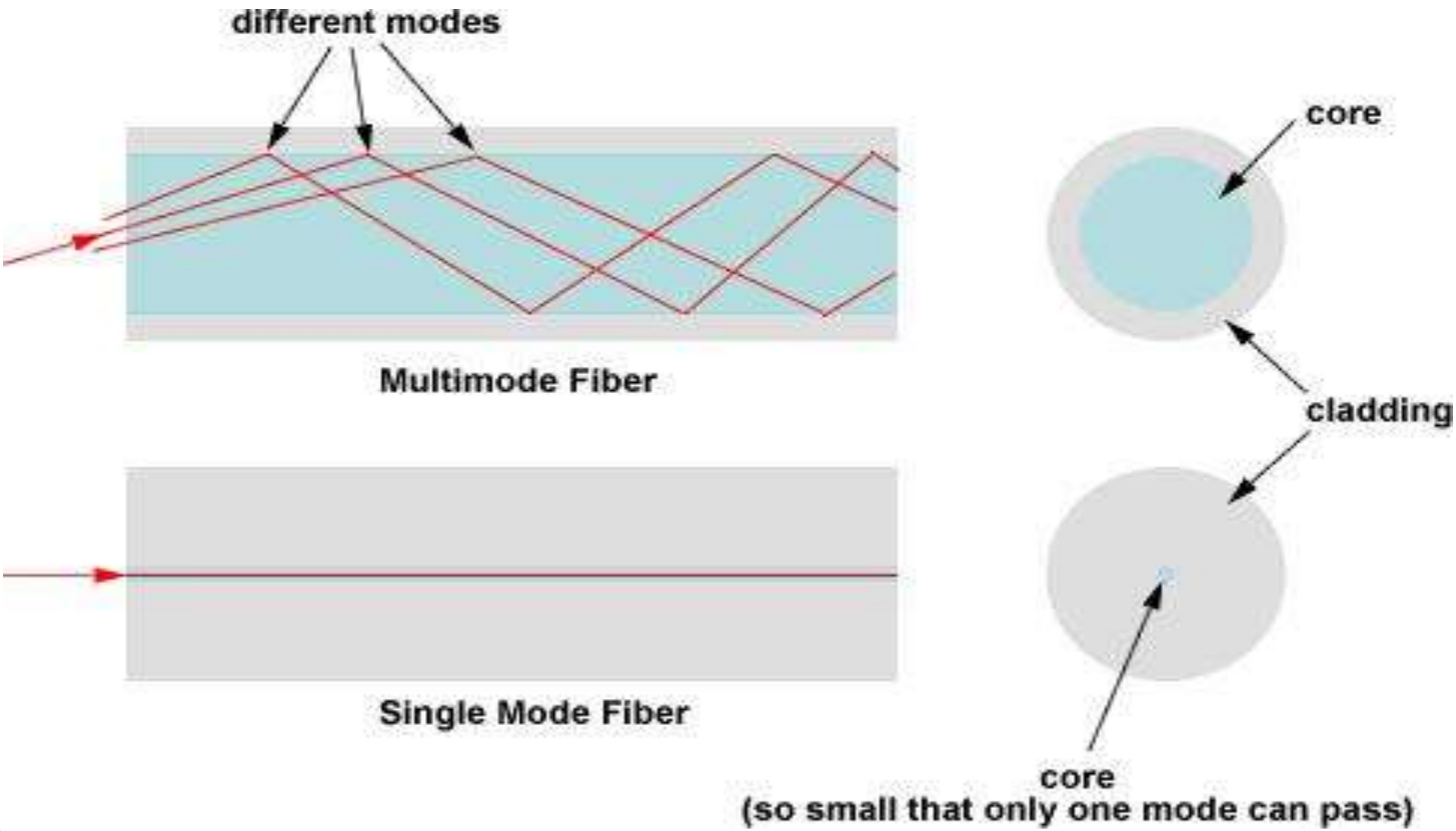
Optical Fiber Modes and Configurations

- The optical fiber is a dielectric waveguide that operates at optical frequency.
- The propagation of light along a waveguide can be described in terms of a set of guided electromagnetic waves called the ***modes***.
- These guided modes are referred to as ***bound*** or ***trapped modes***.
- Only certain discrete number of modes can propagate along fiber.
- Modes satisfies the homogeneous equation in the fiber and boundary conditions a the surface.

modes and configurations



Single mode and multimode



Single mode Step index Fiber:

- Core size is small. Typical core sizes are 2 to 15 μm.
- Only one mode can propagate through the cable.
- Single mode fiber is also known as ***fundamental or mono mode fiber.***
- Does not suffer from mode delay differences(Dispersion)

Multimode step Index Fiber:

- Core size is small. Typical core sizes are 50 to 1000 μm.
- Multiple modes can propagate through the cable.
- Suffer from mode delay differences(Dispersion).Txn BW is low

Graded-Index Multimode Fiber:

- Core refractive index diminishes gradually from the center axis out toward the cladding.
- The core size is varying from 50 to 100 μm.
- The light ray is propagated through the refraction
- The light ray enters the fiber at many different angles
- Minimizing dispersion losses.

Based on the index profile the optical fibers are two types

- **Step-index fibers**
- **Graded-index**

- **Step-index fibers:** Index of refraction changes radically between the core and the cladding.

$$n(r) = \begin{cases} n_1 & \text{when } r < a \text{ (core)} \\ n_2 & \text{when } r \geq a \text{ (cladding)} \end{cases}$$

- **Graded-index fibers:** The index of refraction gradually decreases away from the center of the core.
- Graded-index fiber has less *dispersion* than a multimode step-index fiber

$$n(r) = \begin{cases} n_1\left[1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]^{1/2} & \text{for } 0 \leq r \leq a \\ n_1(1 - 2\Delta)^{1/2} \simeq n_1(1 - \Delta) = n_2 & \text{for } r \geq a \end{cases}$$

Single mode fiber structure

Single mode fibers can be constructed by

- ***Core diameter be a few wavelengths(usually 8-12)***
- ***Small index difference***
- ***Large variations in values of the physical size of core a and index difference Δ.***
- ***V-Number< 2.4***
- *Example: For typical single mode fiber a=3μm, NA=0.1 and λ=0.8μm*

Yields V=2.356

Continued……

Mode Field Diameter

- In single mode fibers geometric distribution of light is important to predict the performance of fiber.
- The mode filed diameter is fundamental parameter of a single mode fiber.
- This parameter is determined from mode field distributions of fundamental LP01 mode.
- The method is how to approximate electric field distribution.
- For a Gaussian distribution, the MFD is given by the 1/e2 width of the optical power
- The Gaussian distribution

$$E(r) = E_0 \exp(-r/W_0)$$

E0=Field at zero radius W_0=Width of electric field distribution

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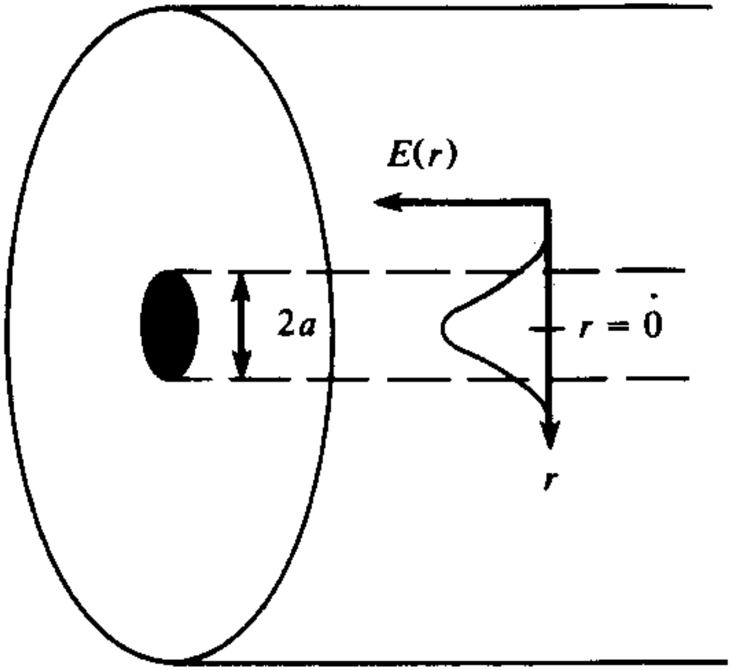

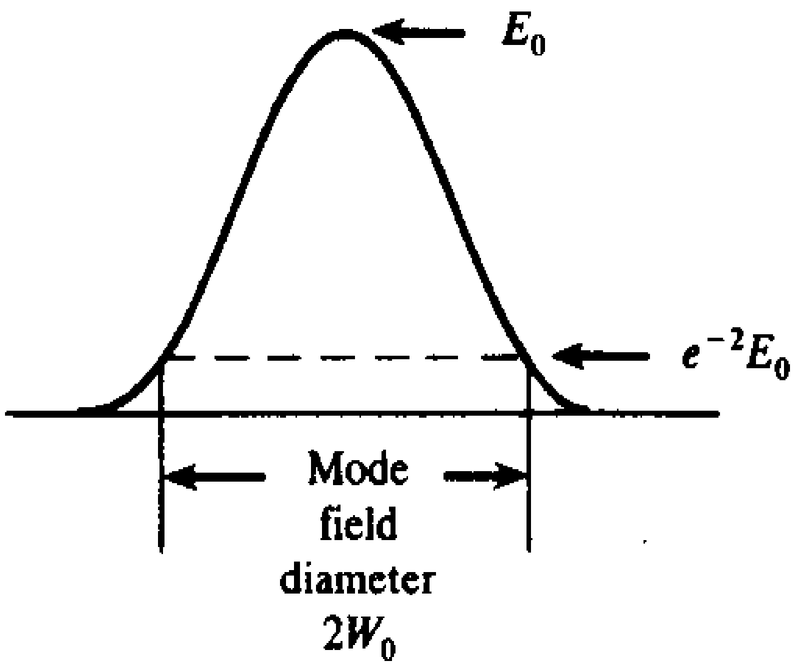

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- The spot size W_0 is gives as –

$$MFD = 2\,W_0$$

Propagation modes in single mode fiber:

- In single mode amplifier, there are two independent degenerate modes.
  - ***Horizontal mode***
  - ***Vertical mode***
- These modes very similar , but their polarization planes are orthogonal
- Constitute fundamental HE_{11} mode
- Modes propagate with equal propagation constants

$$(Kx=Ky)$$

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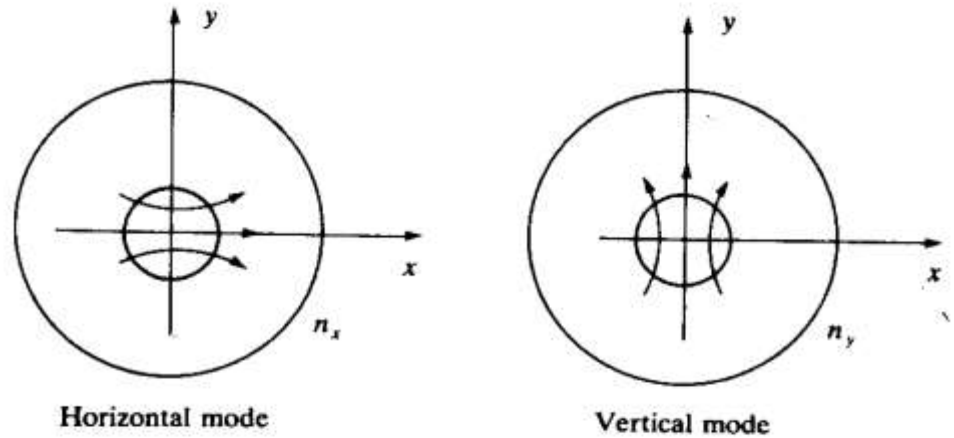


- The modes propagating with different phase velocities and the difference between their effective refractive indices is called the fiber ***birefringence*.**

$$B_f = n_y - n_x$$

- **Similarly ,the birefringence may define as**

$$\beta = k_0(n_y - n_x)$$

$k_0 = 2\pi/\lambda$ is the free space propagation

Graded –Index fiber Structure

- The index of refraction gradually decreases with increasing radial distance r from center, but constant in the cladding.
- Refractive index variation in core

$$n(r) = \begin{cases} n_1\left[1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]^{1/2} & \text{for} \quad 0 \le r \le a \\ n_1(1 - 2\Delta)^{1/2} \simeq n_1(1 - \Delta) = n_2 & \text{for} \quad r \ge a \end{cases}$$

α Indicates shape of index profile.

- Index difference

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \simeq \frac{n_1 - n_2}{n_1}$$

- The total numerical aperture is

$$\mathrm{NA}(r) = \begin{cases} \left[n^2(r) - n_2^2\right]^{1/2} \simeq \mathrm{NA}(0)\sqrt{1 - (r/a)^{\alpha}} & \text{for} \quad r \le a \\ 0 & \text{for} \quad r > a \end{cases}$$

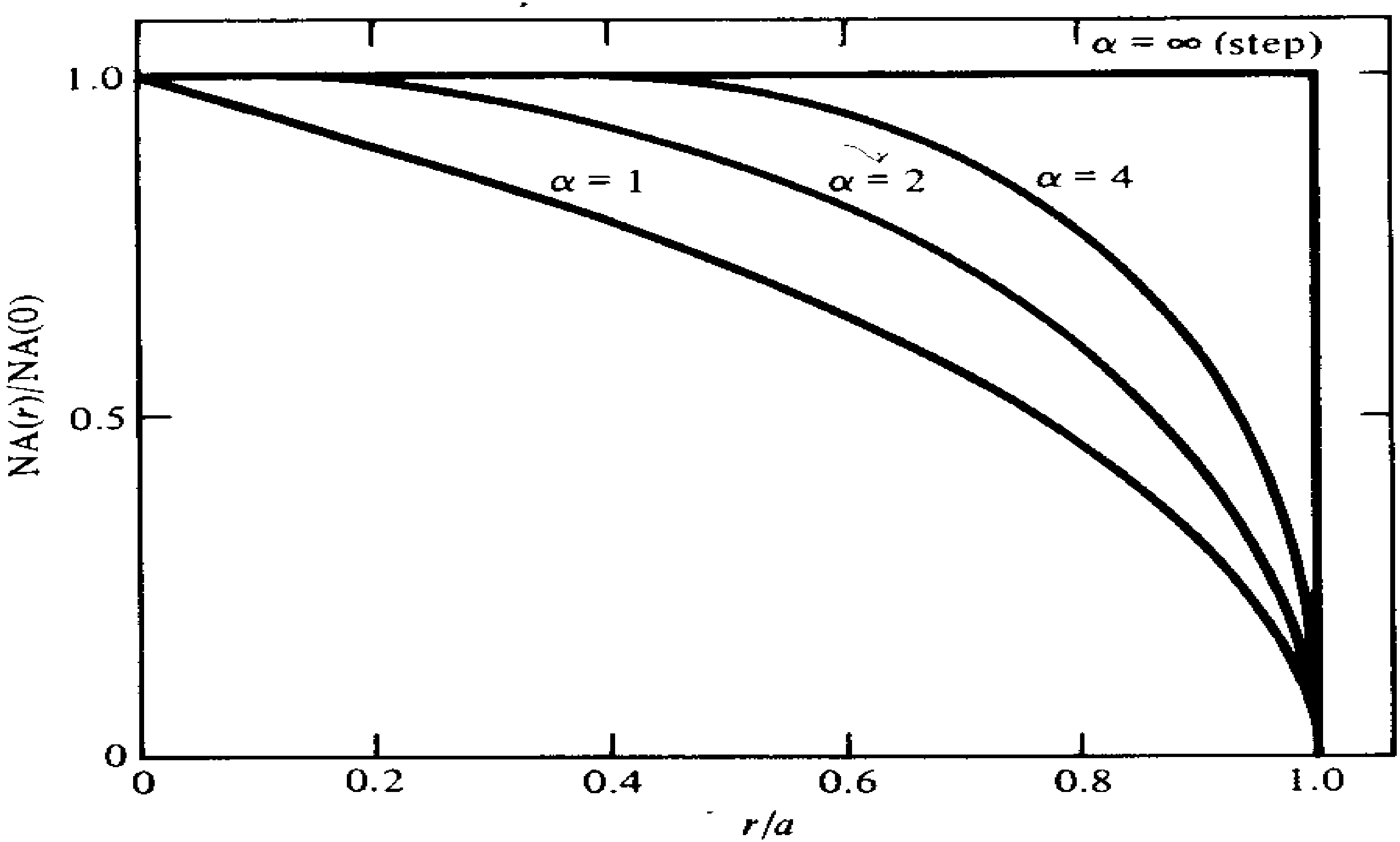
- Axial numerical aperture is define as

$$\mathrm{NA}(0) = \left[n^2(0) - n_2^2\right]^{1/2} = \left(n_1^2 - n_2^2\right)^{1/2} \simeq n_1\sqrt{2\Delta}$$

TRANSMISSION CHARACTERISTICS OF OPTICAL FIBERS

There are 2 main characteristics of optical fiber

- Signal attenuation
- Signal distortion



Comparison of NA for fibers having various α profiles.

Signal Attenuation

It determines the maximum ***unamplified or repeaterless distance*** between transmitter and receiver.

Signal Distortion

- Causes optical ***pulses broaden***.
- Overlapping with neighboring pulses, creating ***errors*** in the receiver output.
- It limits the ***information carrying capacity*** of a fiber.

Attenuation

***Attenuation is a measure of decay of signal strength or loss of light power that occurs as light pulses propagate through the length of the fiber*.**

Attenuation Units: **As light propagates through the fiber, its power decreases with distance. Let the couples optical power is p(0) i.e. at origin (z = 0). Then the power at distance z is given by,**

$$P(z) = P(0)e^{-\alpha_p z}$$

$$P(l) = P(0)e^{-\alpha_p l}$$ mw

Where, αp is fiber attenuation constant (per km).

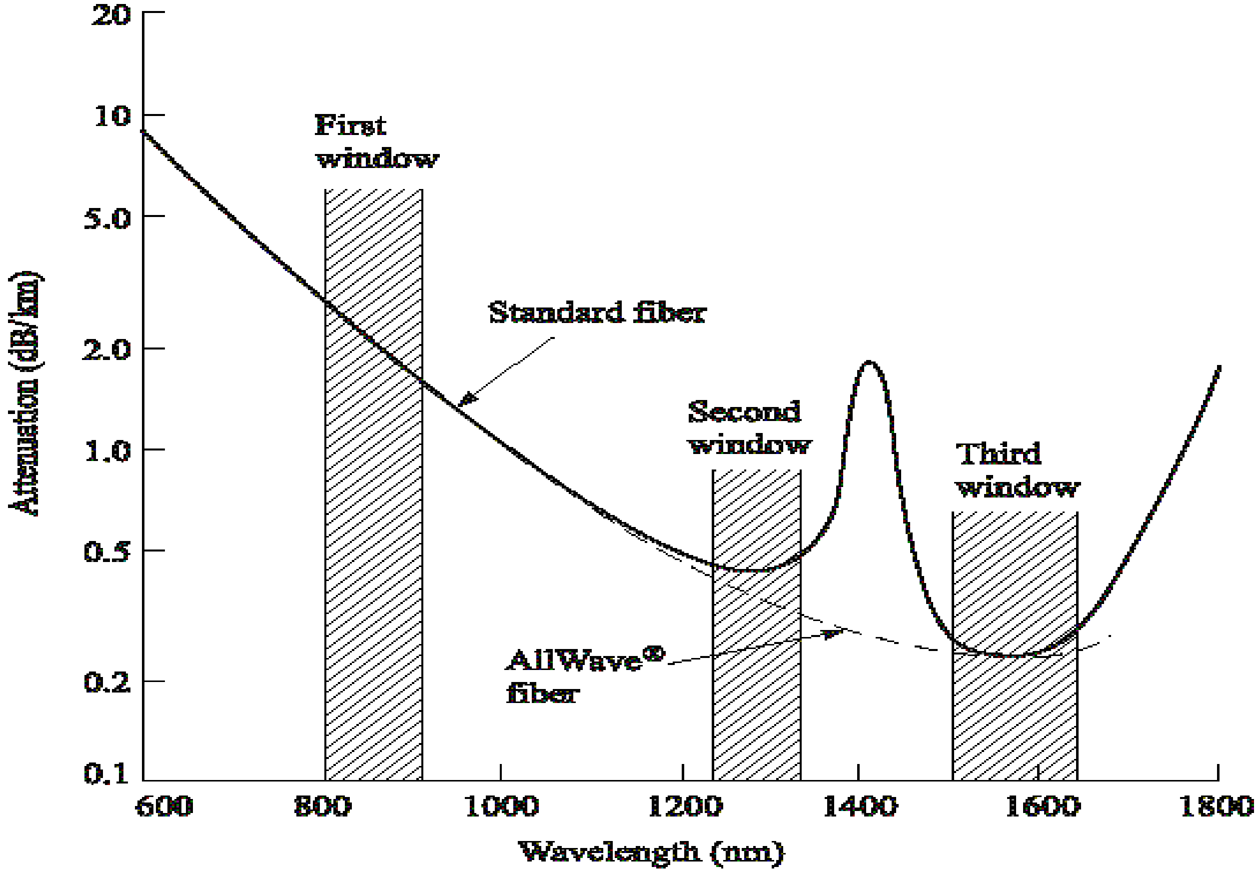
$$\alpha_p = \frac{1}{z} \ln\left[\frac{P(0)}{P(z)}\right]$$

$$\alpha_{dB/km} = 10 . \frac{1}{z} \log\left[\frac{P(0)}{P(z)}\right]$$

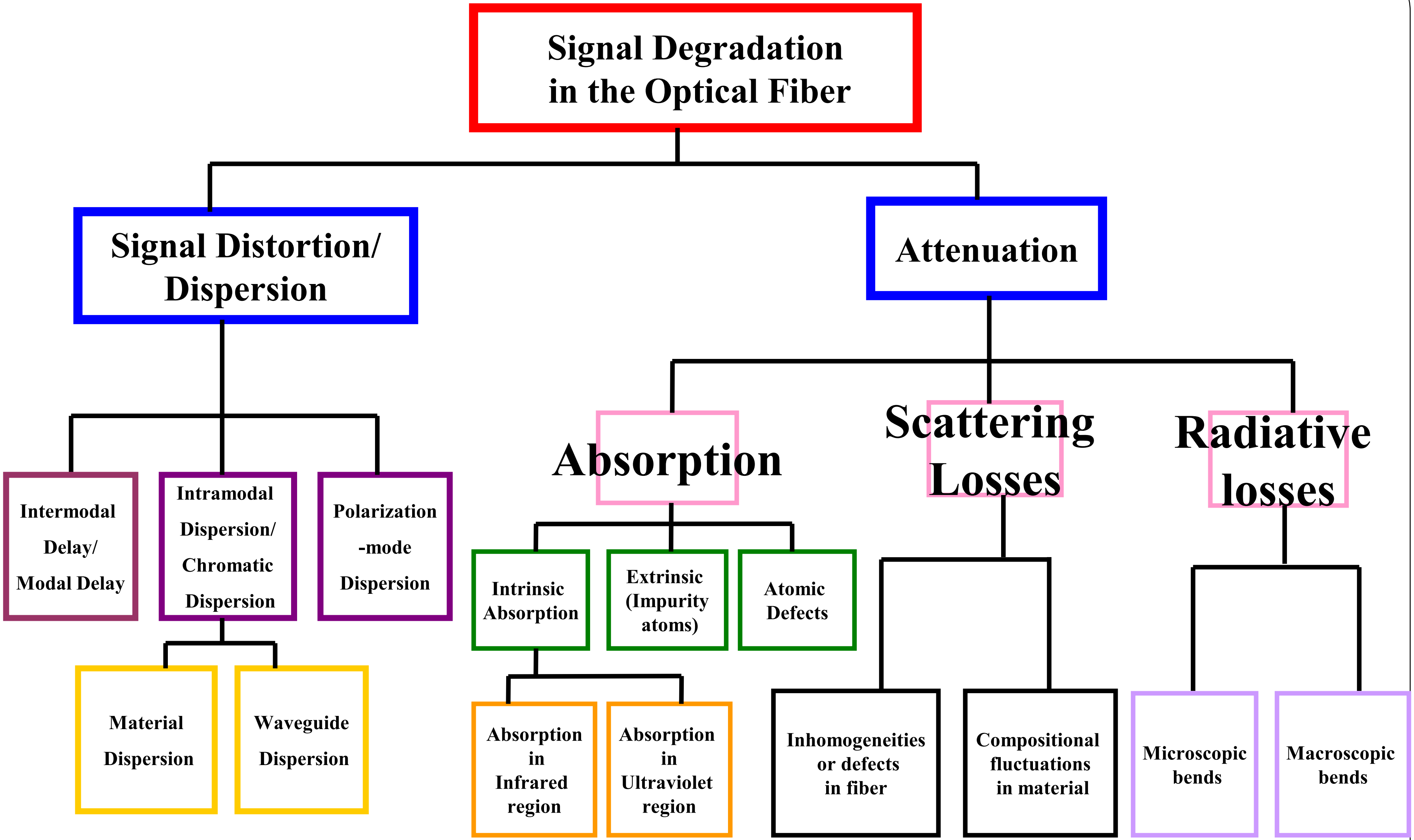
$$\alpha_{dB/km} = 4.343 \ \alpha_p \text{ per km}$$

This parameter is known fiber loss or fiber attenuation.

Attenuation as a function of Wavelength



Optical fiber attenuation as a function of wavelength yields nominal values of 0.5 dB/km at 1310 nm and 0.3 dB/km at 1550 nm for standard single mode fiber. Absorption by the water molecules causes the attenuation peak around 1400nm for standard fiber. The dashed curve is the attenuation for low water peak fiber.


Signal Degradation in the Optical Fiber
Signal Distortion/ Dispersion
Attenuation
Intermodal Delay/ Modal Delay
Intramodal Dispersion/ Chromatic Dispersion
Polarization -mode Dispersion
Material Dispersion
Waveguide Dispersion
Absorption
Scattering Losses
Radiative losses
Intrinsic Absorption
Extrinsic (Impurity atoms)
Atomic Defects
Absorption in Infrared region
Absorption in Ultraviolet region
Inhomogeneities or defects in fiber
Compositional fluctuations in material
Microscopic bends
Macroscopic bends

Attenuation

The Basic attenuation mechanisms in a fiber:

1. **Absorption:**

   It is related to the fiber material.

2. **Scattering:**

   It is associated both with the fiber material and with the structural imperfections in the optical waveguide.

3. **Radiative losses/ Bending losses:**

   It originates from perturbation (both microscopic and macroscopic) of the fiber geometry.

Absorption

Absorption is caused by three different mechanisms:

1. Absorption by atomic defects

2. Extrinsic Absorption

3. Intrinsic absorption

1. Absorption by atomic defects

Atomic defects are imperfections in the atomic structure of the fiber material.

Examples:

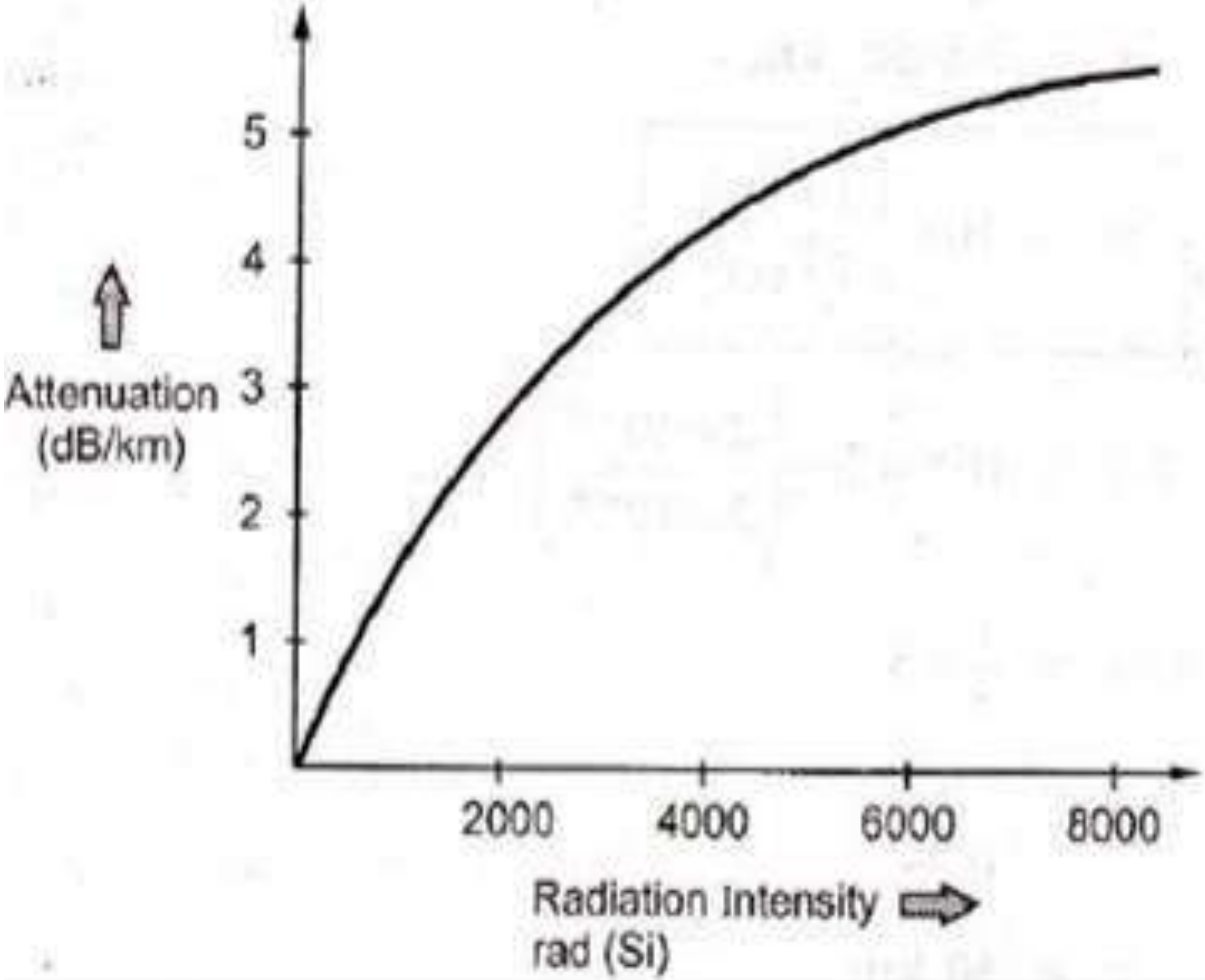
•Missing molecules

•High density clusters of atom groups

•Oxygen defects in the glass structure.

•Absorption losses arising from these defects are **negligible** compared with intrinsic and impurity absorption.

•Can be significant if the fiber is exposed to ionization radiations.



1 rad(Si) = 0.01 J/Kg

Absorption

2. Extrinsic absorption by impurity atoms

The dominant absorption factor in silica fibers is the presence of **minute quantities of impurities** in the fiber material.

- **These impurities include**
  - OH- (water) ions dissolved in the glass.
  - Transition metal ions, such as iron, copper, chromium and vanadium

Absorption

3. Intrinsic absorption by the basic constituent atoms

Intrinsic absorption is associated with the basic fiber material (e.g pure SiO_2).

<u>Intrinsic absorption results from:</u>

1. Electronic absorption bands in the ***<u>ultraviolet region</u>***
2. Atomic vibration bands in the near ***<u>infrared region</u>***

<u>Electronic absorption (EA)</u> occurs when a photon interacts with an electron in the valance band and excites it to a higher energy level.

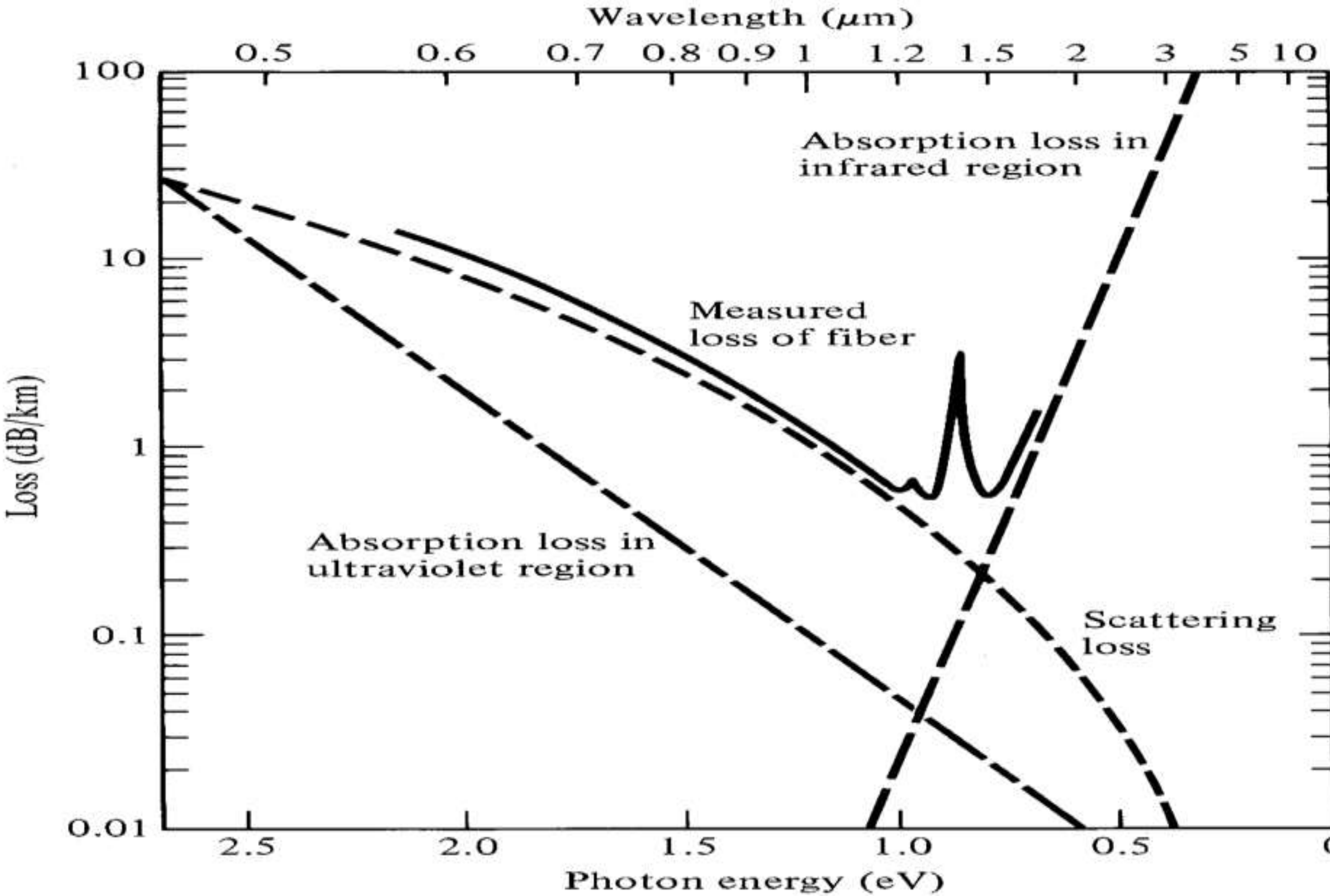
The electronic absorption is associated with the band gap of the material.

$$\alpha_{uv} = \frac{154.2x}{46.6x + 60} \times 10^{-2} \exp\left(\frac{4.63}{\lambda}\right)$$

where, x is mole fraction of GeO_2, λ is operating wavelength.

<u>The infrared absorption</u> is associated with the vibration frequency of chemical bond between the atoms of which the fiber is composed.

$$\alpha_{IR} = 7.81 \times 10^{11} \times \exp\left(\frac{-48.48}{\lambda}\right)$$



Optical fiber attenuation characteristics and their limiting mechanisms for a GeO_2 doped low loss water content silica fiber.

Scattering Losses

Scattering losses in glass arise due to

1. Compositional fluctuations

2. Inhomogeneities or defects occurring during fiber manufacture

➢These two effects give rise to refractive index variation, within the glass over distances.

➢These index variation case Rayleigh-type scattering of the light and *inversely proportional to wavelength*.

➢It decreases dramatically with increasing wavelength.

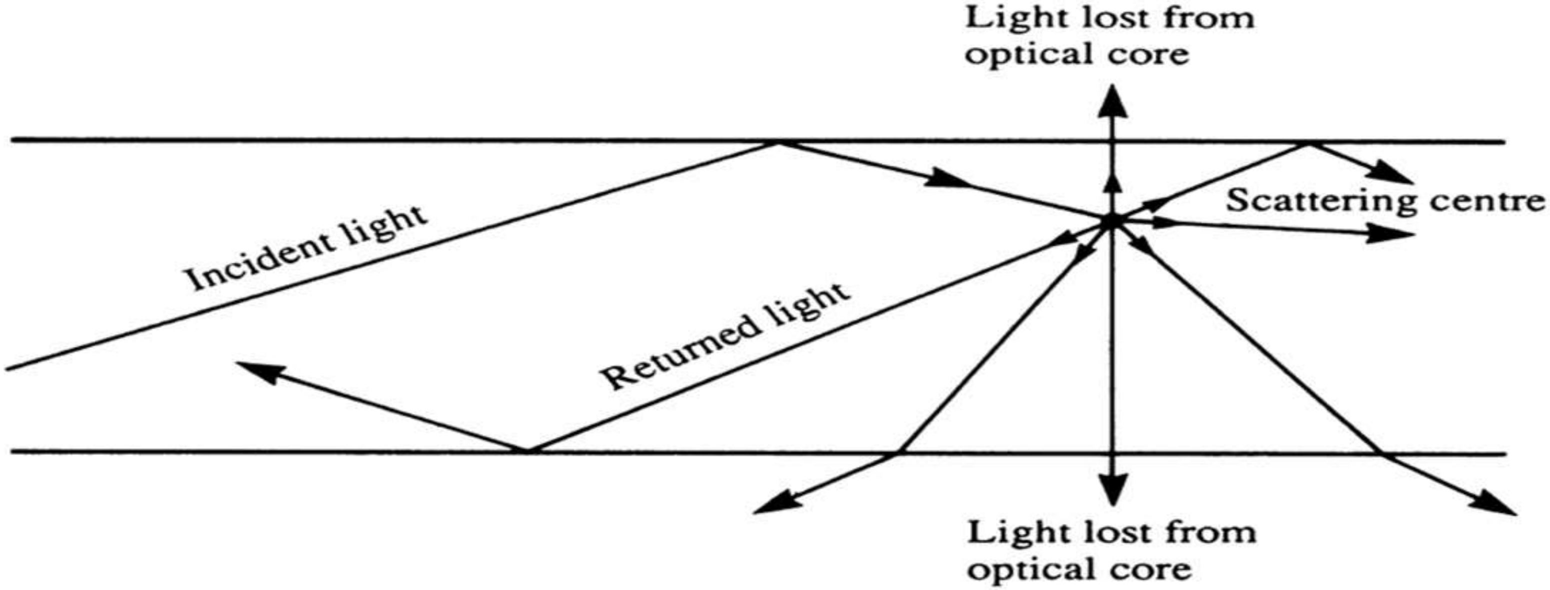
Scattering loss for single component glass is given by,

$$\alpha_{scat} = \frac{8\pi^3}{3\lambda^4}(n^2-1)^2 k_B T_f \beta_T \text{ nepers}$$

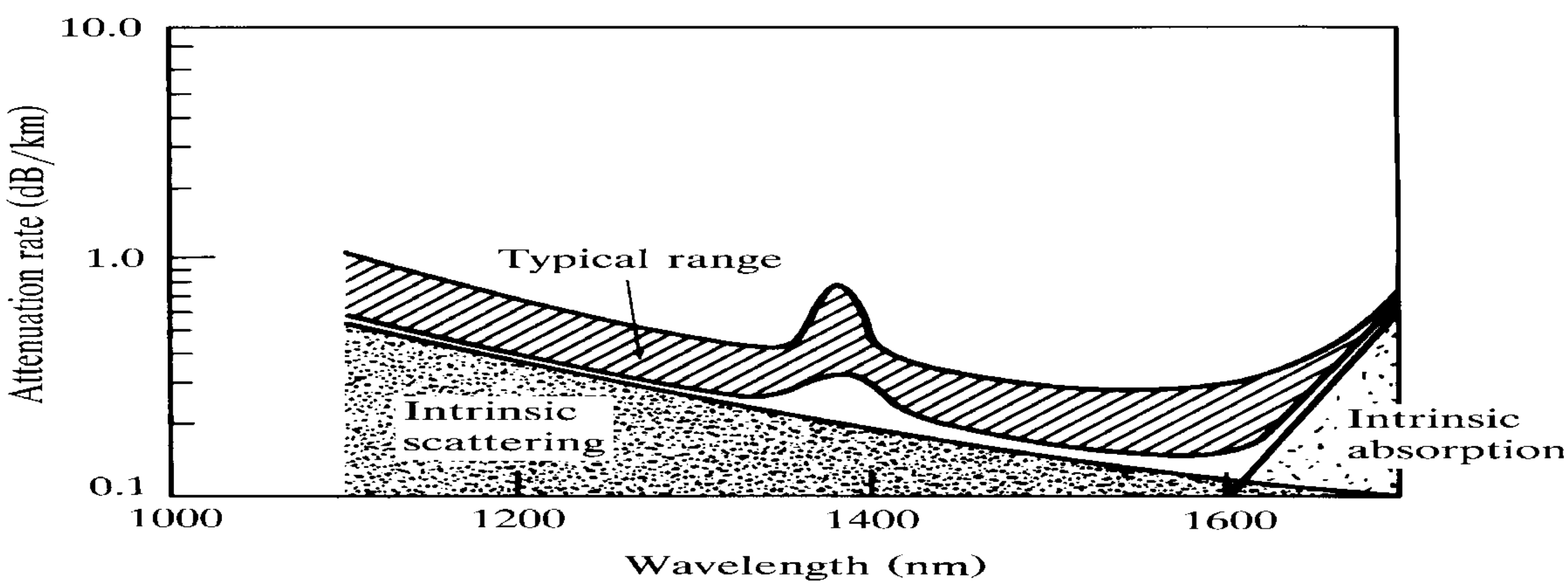
where, n = Refractive index, K_B = Boltzmann's constant

β_T = Isothermal compressibility of material

T_f = Temperature at which density fluctuations are frozen into the glass as it solidifies



Rayleigh scattering in an optical fiber



Combining the infrared, ultraviolet, and scattering losses for single mode fiber.

Radiative losses / Bending Losses

Radiative losses occur whenever an optical fiber undergoes a bend of finite radius of curvature.
Fiber can be subject to two types of bends:

1.Macroscopic bends
2.Microscopic bends

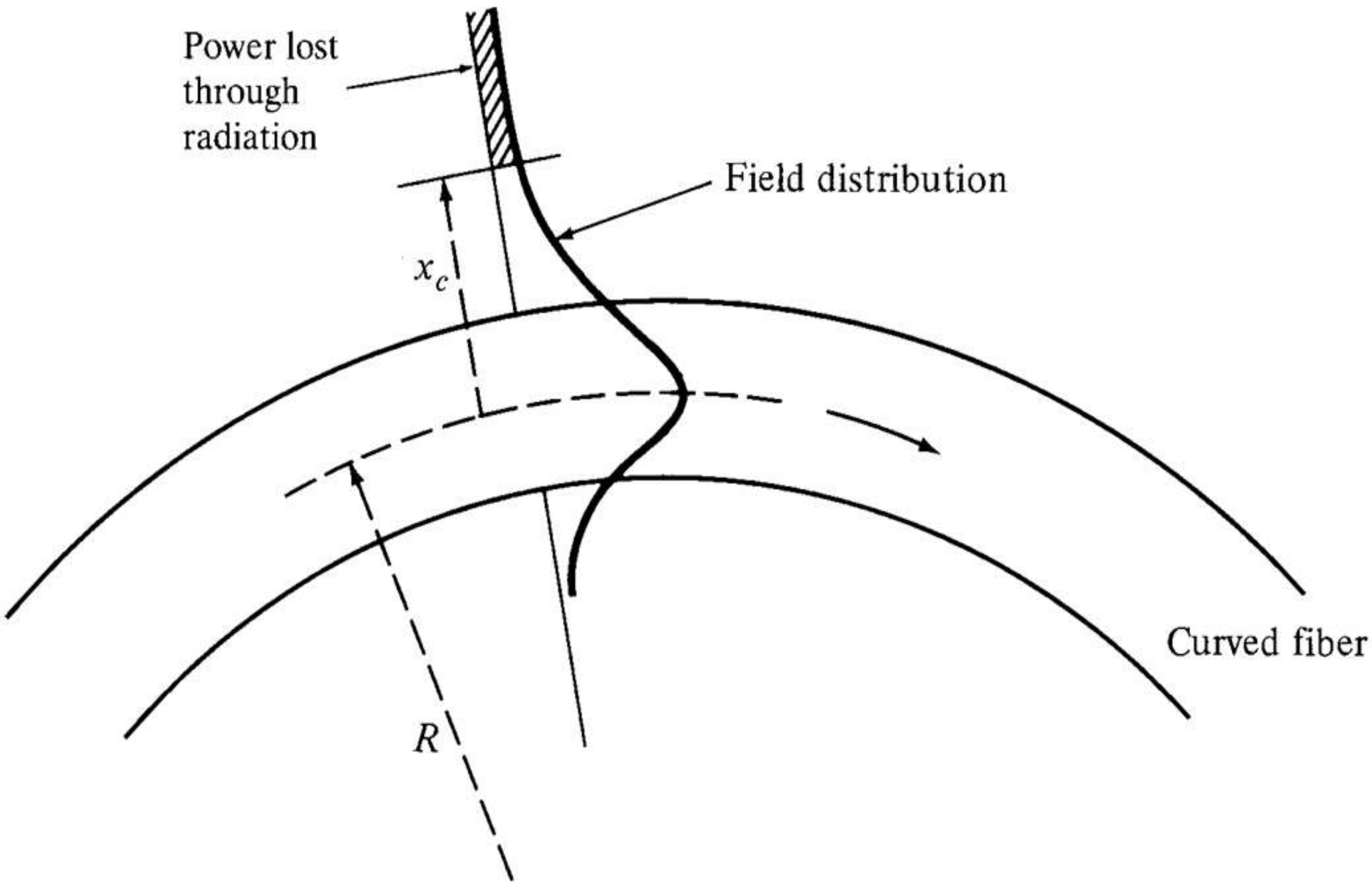
1. Macrobending losses or bending loss:

- Losses due to ***curvature*** and an ***abrupt change in radius*** of curvature.

  Ex: Fiber turning edge of the room.

- Radiation losses depend on the value radius of curvature R

- As the lower order modes remain ***close to the core axis*** and the higher modes are ***closer to the cladding*** so the higher modes will radiate out of the fiber first



Macro bending

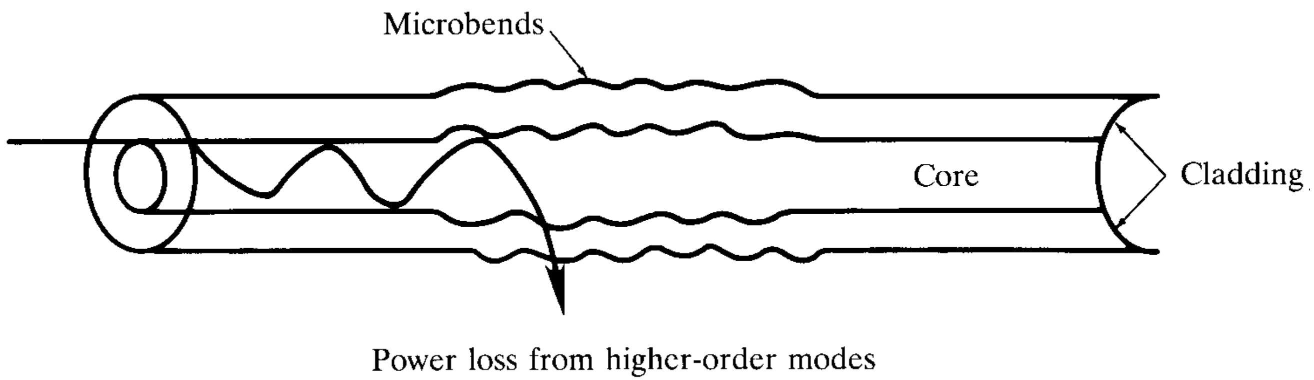
Radiative losses / Bending Losses

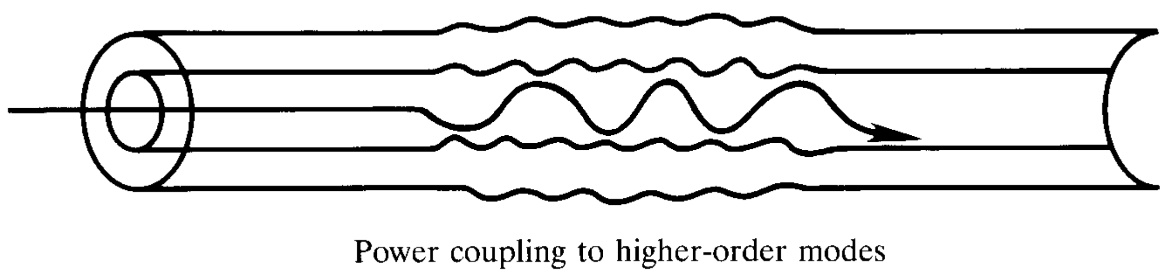
Microbending losses:

- Microbending is a loss due to ***small bending or distortions***
- Microbends are repetitive small scale fluctuations in radius of curvature of the fiber axis.
- Microbends causes repetitive coupling of energy between the ***guided modes*** and the ***leaky*** *or* ***nonguided modes*** in the fiber.

Caused by:

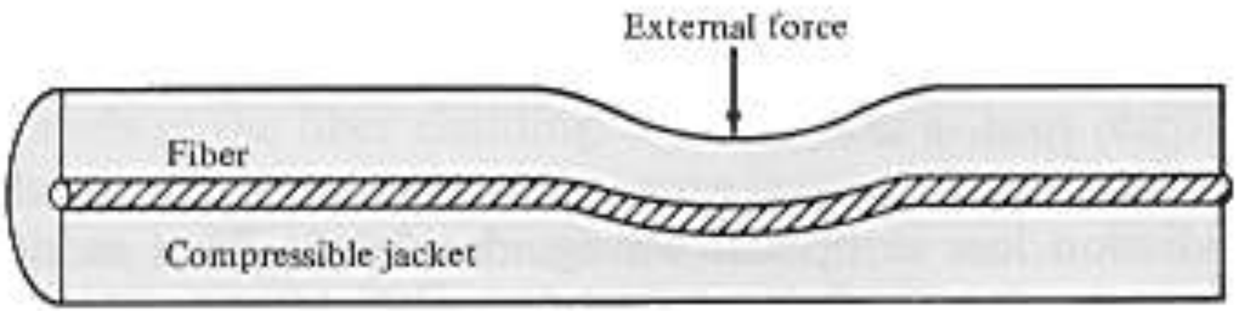
- Nonuniformities in the manufacturing of the fiber
- Nonuniform lateral pressures during cabling
- High pressures



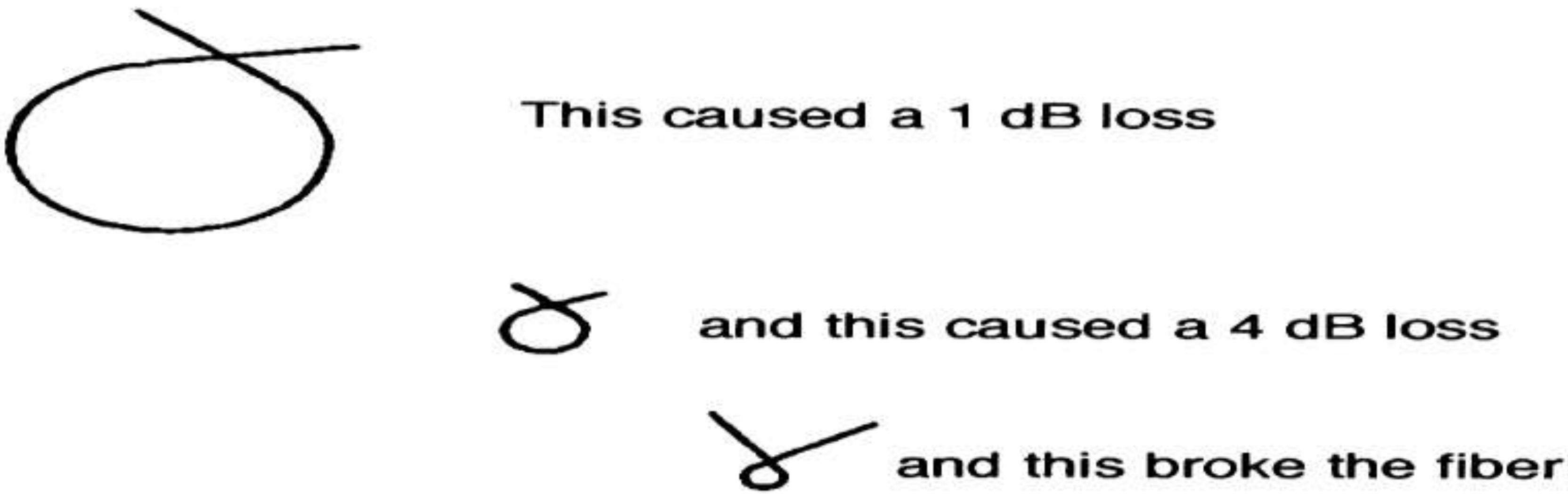


Microbending losses

Minimizing microbending losses:



A compressible jacket extruded over a fiber reduces microbending resulting from external forces.



Bends are shown full size — and may have caused damage to the fiber

Core and Cladding Losses

- Since the core and cladding have different indices of refraction hence they have different attenuation coefficients ***α1 and α2*** respectively
- For step index fiber, the loss for a mode order (v, m) is given by,

$$\alpha_{vm} = \alpha_1 \frac{P_{core}}{P} + \alpha_2 \frac{P_{cladding}}{P}$$

- For low-order modes, the expression reduced to

$$\alpha_{vm} = \alpha_1 + (\alpha_2 + \alpha_1) \frac{P_{cladding}}{P}$$

where, $\frac{P_{core}}{P}$ and $\frac{P_{cladding}}{P}$ are fractional powers.

- For graded index fiber, loss at radial distance is expressed as,

$$\alpha(r) = \alpha_1 + (\alpha_2 - \alpha_1) \frac{n^2(0) - n^2(r)}{n^2(0) - n_2^2}$$

- The loss for a given mode is expressed by,

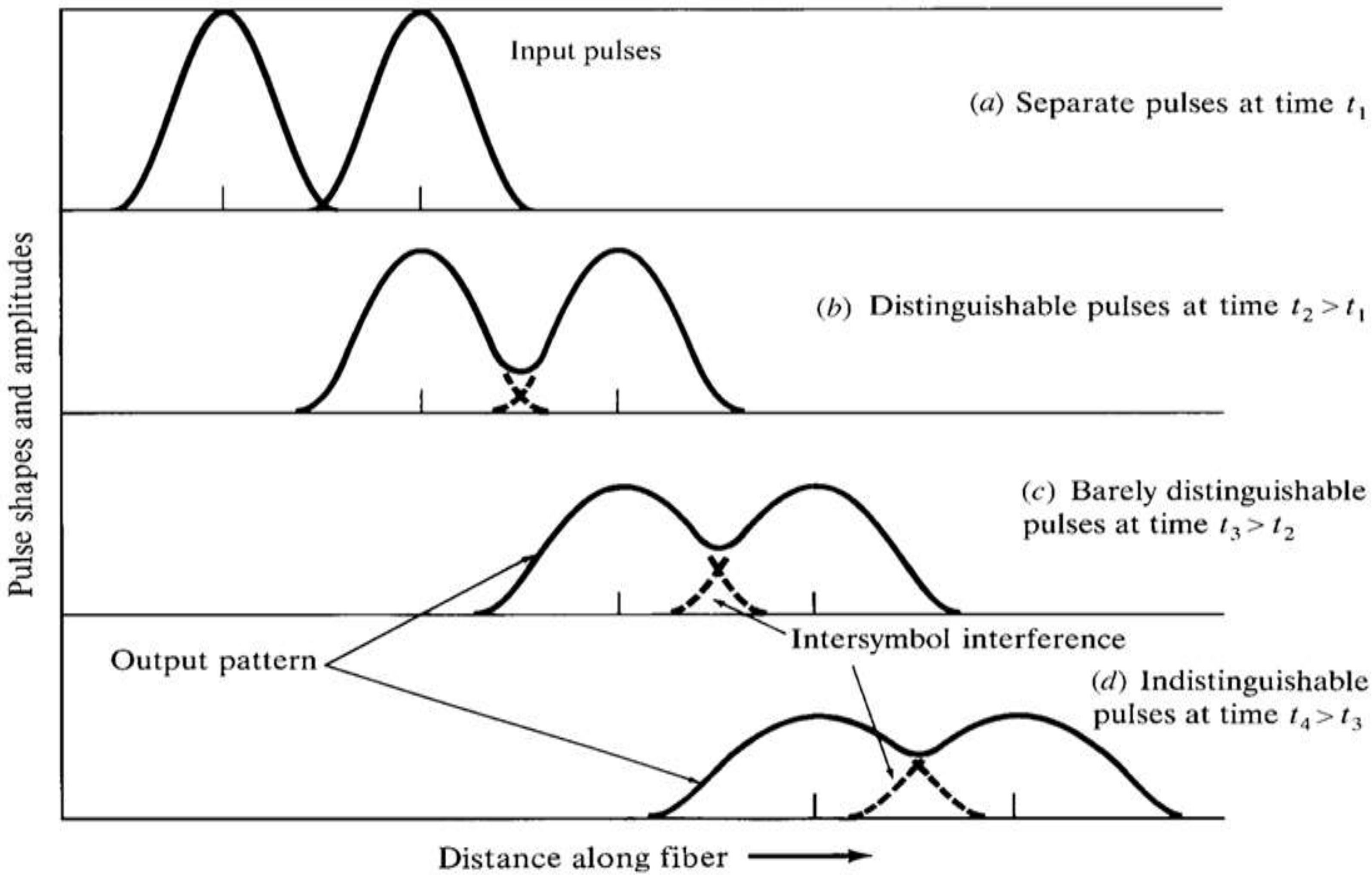
$$\alpha_{Graded\ Index} = \frac{\int_0^\infty \alpha(r)\, P(r)\, r\, dr}{\int_0^\infty P(r)\, r\, dr}$$

- Where, P(r) is power density of that model at radial distance r.

Signal Distortion in Fibers

Optical signal weakens from attenuation mechanisms and broadens due to distortion effects.

- The pulse gets distorted as it travels along the fiber lengths as consequence of ***pulse spreading***.
- Pulse spreading in fiber is referred ***as dispersion***
- Dispersion is caused by *difference in the propagation times* of light rays that takes different paths during the propagation.
- Dispersion limits the ***information bandwidth***



Pulse Broadening And Attenuation

Information Capacity Determination

Information capacity of an optical fiber is specified by the ***bit rate-distance*** product **BL**.

- Pulse spread should be less than the width of a bit period

  $\Delta T < 1/B$ General requirement

  $\Delta T \leq 0.1/B$ For high performance link

Bit rate distance product $BL < n_2 c / n_1^2 \Delta$

Group Delay: The group delay in an optical device is **the time delay for a pulse to pass it.** Group delay per unit length can be defined as

$$1/V_{g}= \frac{\tau_g}{L} = \frac{d\beta}{d\omega} = \frac{1}{c}\frac{d\beta}{dk} = -\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda}$$

Where v_g is the ***group velocity*** at which energy in pulse travels in fiber.

The total delay difference $\delta\tau$ over a distance L is:

$$\delta\tau = \left|\frac{d\tau_g}{d\lambda}\right|\delta\lambda = -\frac{L}{2\pi c}\left(2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right)\delta\lambda$$

$$= \left|\frac{d\tau}{d\omega}\right|\delta\omega = \frac{d}{d\omega}\left(\frac{L}{V_g}\right)\delta\omega = L\left(\frac{d^2\beta}{d\omega^2}\right)\delta\omega$$

$\beta_2 \equiv \frac{d^2\beta}{d\omega^2}$ is called ***GVD parameter***, and shows how much a light pulse broadens as it travels along an optical fiber.

The more common parameter is called ***Dispersion***, and can be defined as the delay difference per unit length per unit wavelength as follows

$$D = \frac{1}{L}\frac{d\tau_g}{d\lambda} = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right) = -\frac{2\pi c}{\lambda^2}\beta_2$$

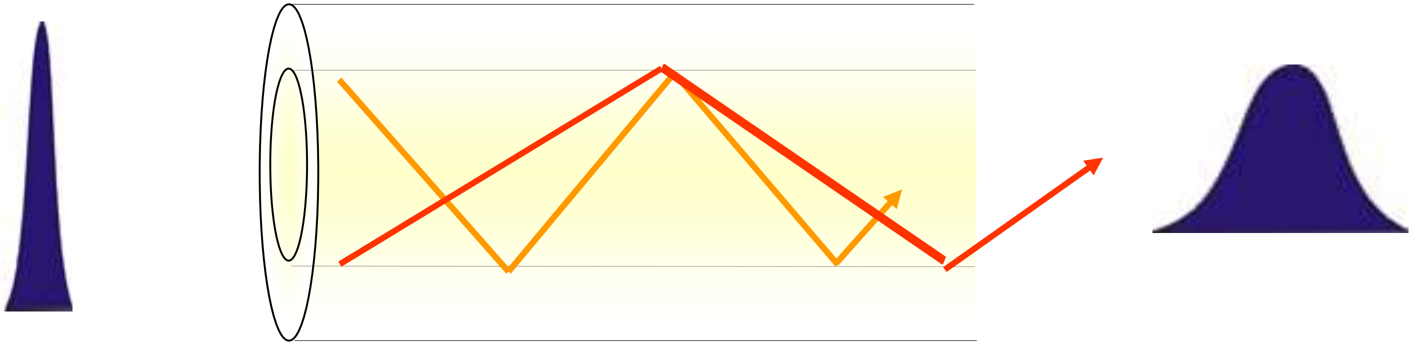
The pulse spreading $\boldsymbol{\sigma_g}$ of fiber length of L, can be well approximated by:

$$\sigma_g \approx \left|\frac{d\tau_g}{d\lambda}\right|\sigma_\lambda = DL\sigma_\lambda$$

D has a typical unit of ***[ps/(nm.km)].***

Dispersion

- Dispersion distorts both pulse and analog modulation signals.
- In a pulse modulated system, this causes the received pulse to be ***spread out*** over a longer period.
- It is noted that actually no power is lost to dispersion, the spreading effect ***reduces the peak power.***



- Pulse dispersion is usually specified in terms of ***"Nanoseconds-per-kilometer".***

Dispersion

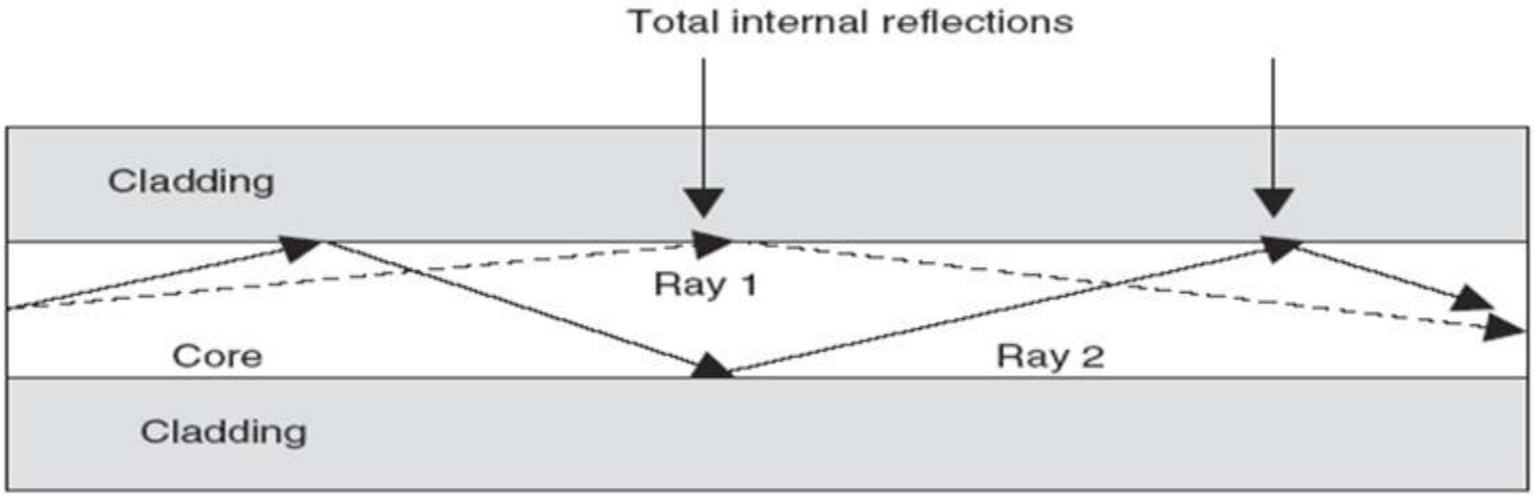
Dispersion occurs due to following mechanisms:

- ***Intermodal Delay or Modal Delay***
- ***Intramodal Dispertion or Chromatic Dispersion***
  - ***Material Dispertion***
  - ***Waveguide Dispertion***
- ***Polarization –Mode Dispersion***

1.Intermodal delay/ modal delay:

- Intermodal distortion or modal delay appears only in multimode fibers. result of each mode having a different value of the group velocity at a single frequency.
- The amount of pulse spreading is a function of the number of modes and length of the fiber
- Broadening of pulse is simply obtained from ray tracing for a fiber of length L:

$$\Delta T = T_{max} - T_{min} = (L n_1 \Delta / c)$$



Light rays with steep incident angles have longer path lengths than lower angle rays.

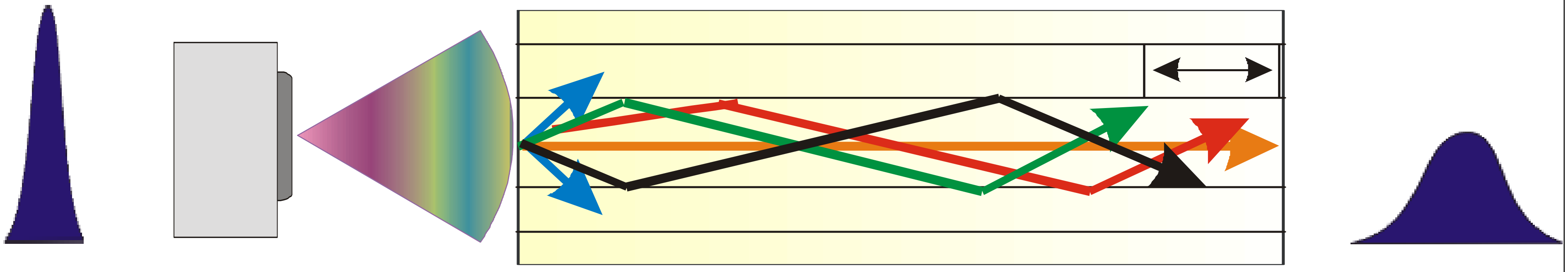
How to minimize the effect of modal dispersion?

1. Graded index fiber 2. Single mode fiber

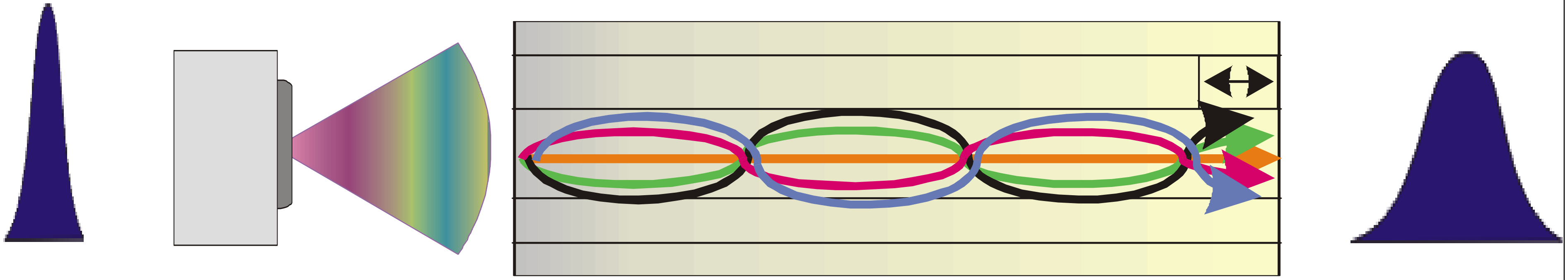
- We could decrease the number of modes ***by increasing the wavelength*** of the light

$$V = 2\pi a / \lambda \times (n_1^2 - n_2^2)^{1/2} = 2\pi a / \lambda \times (NA)$$

- ***Change in the numerical aperture*** can help but it only makes a marginal improvement.
- ***The smaller the core,*** the fewer the modes.



Step Index Multi-mode



Graded Index Multi-mode

Intramodal Dispersion or Chromatic Dispersion

- This takes place within a single mode.
- Intramodal dispersion depends on *the* ***wavelength****,* its effect on signal distortion ***increases*** with the ***spectral width*** of the light source.

Two main causes of intramodal dispersion are as:

1. **Material Dispersion**
2. **Waveguide Dispersion**

1.Material Dispersion:

- Occurs due to refractive index of the material varies as a function of wavelength. $n(\lambda)$
- Material-induced dispersion for a plane wave propagation in homogeneous medium of refractive index *n*:

$$\tau_{mat} = L\frac{d\beta}{d\omega} = -\frac{\lambda^2}{2\pi c}L\frac{d\beta}{d\lambda} = -\frac{\lambda^2}{2\pi c}L\frac{d}{d\lambda}\left[\frac{2\pi}{\lambda}n(\lambda)\right]$$

$$= \frac{L}{c}\left(n - \lambda\frac{dn}{d\lambda}\right)$$

- The pulse spread due to material dispersion is therefore:

$$\sigma_g \approx \left|\frac{d\tau_{mat}}{d\lambda}\right|\sigma_\lambda = \frac{L\sigma_\lambda}{c}\left|\lambda\frac{d^2n}{d\lambda^2}\right| = L\sigma_\lambda\left|D_{mat}(\lambda)\right|$$

$D_{mat}(\lambda)$ is material dispersion

Material dispersion can be reduced:

- Either by choosing sources with narrower spectral output widths OR
- By operating at longer wavelengths.

Waveguide Dispersion:

- Waveguide dispersion is due to the dependency of the group velocity of the fundamental mode as well as other modes on the *V* number.
- Let consider that *n* is not dependent on wavelength.
- Defining the normalized propagation constant *b* as:

$$b = \frac{\beta^2 / k^2 - n_2^{\ 2}}{n_1^{\ 2} - n_2^{\ 2}} \approx \frac{\beta / k - n_2}{n_1 - n_2}$$

- solving for propagation constant:

$$\beta \approx n_2 k(1 + b\Delta)$$

- Using *V* number:

$$V = ka(n_1^{\ 2} - n_2^{\ 2})^{1/2} \approx kan_2\sqrt{2\Delta}$$

- Delay time due to waveguide dispersion can then be expressed as:

$$\tau_{wg} = \frac{L}{c}\left[n_2 + n_2\Delta\frac{d(Vb)}{dV}\right]$$

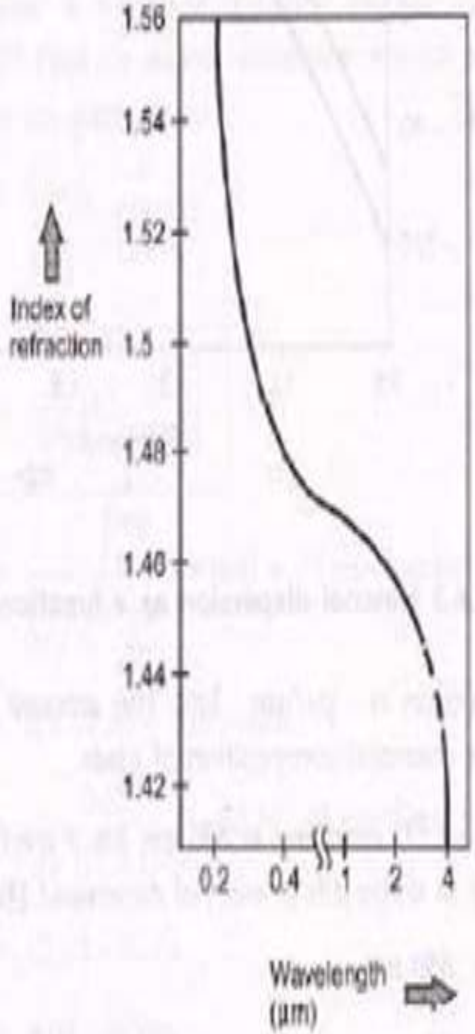
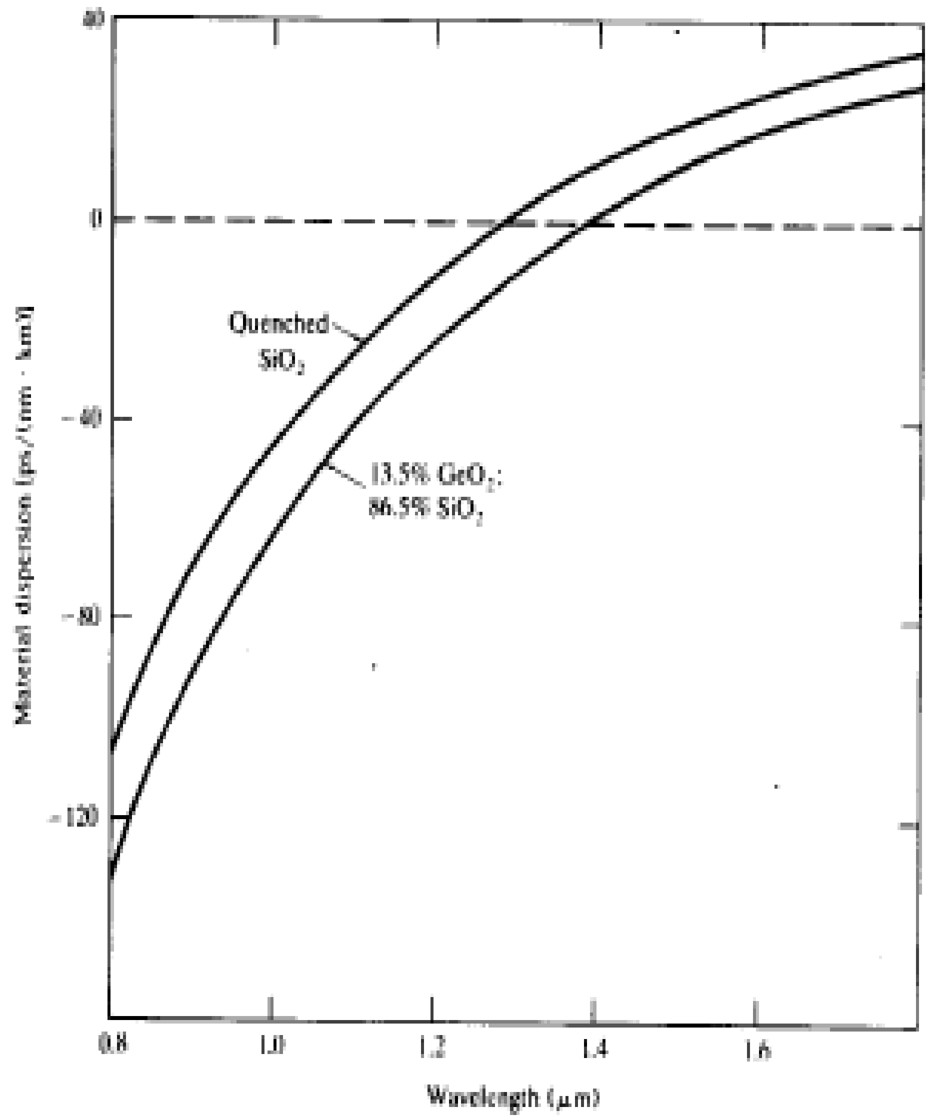


Fig. 2.6.2 Index of refraction as a function of wavelength



Material dispersion as a function of optical wavelength for pure silica and 13.5 percent GeO_2/ 86.5 percent SiO_2.

Total Dispersion, zero Dispersion

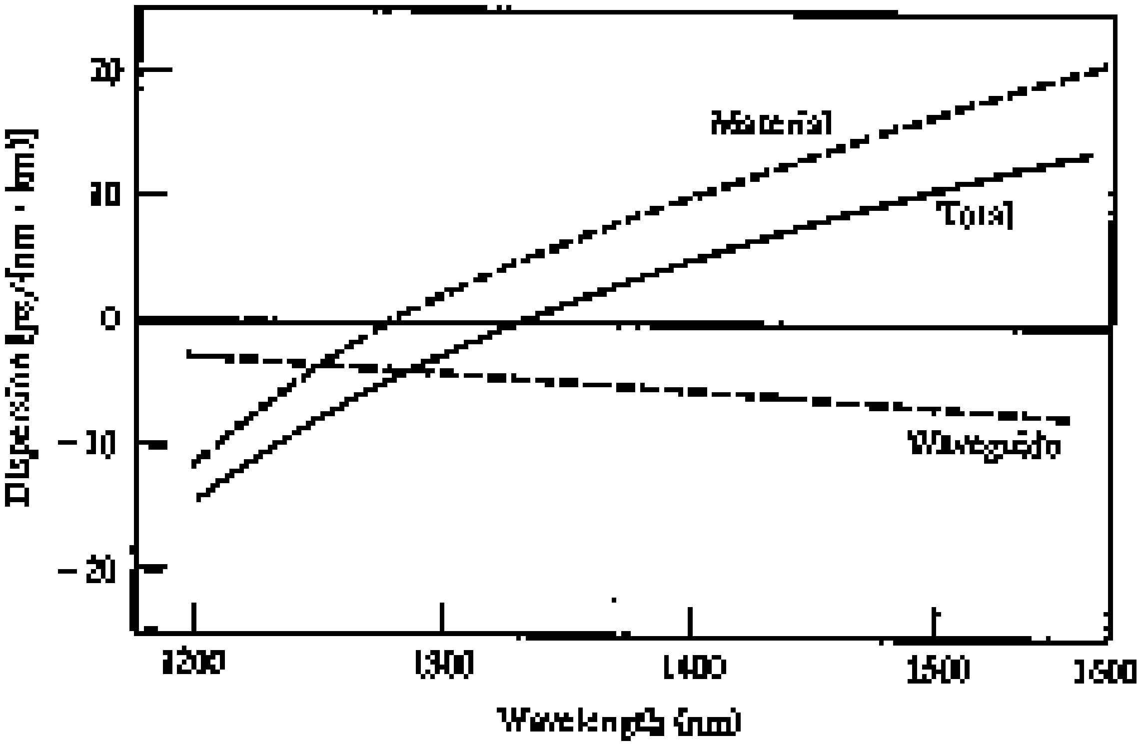


FIGURE 3-16
Examples of the magnitudes of material and waveguide dispersion as a function of optical wavelength for a single-mode fused-silica-core fiber. (Reproduced with permission from Keck,[16] © 1985, IEEE.)

Fact 1) Minimum distortion at wavelength about 1300 nm for single mode silica fiber.
Fact 2) Minimum attenuation is at 1550 nm for sinlge mode silica fiber.
Strategy: shifting the zero-dispersion to longer wavelength for minimum attenuation and dispersion.

Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

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- *http://en.wikipedia.org/wiki/Optical_communication*
- http://www.journals.elsevier.com/optics-communications/

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Department of Electronics and Communication Engineering

OPTICAL FIBER COMMUNICATION

Unit-II

Fiber Optical Sources and coupling

Contents

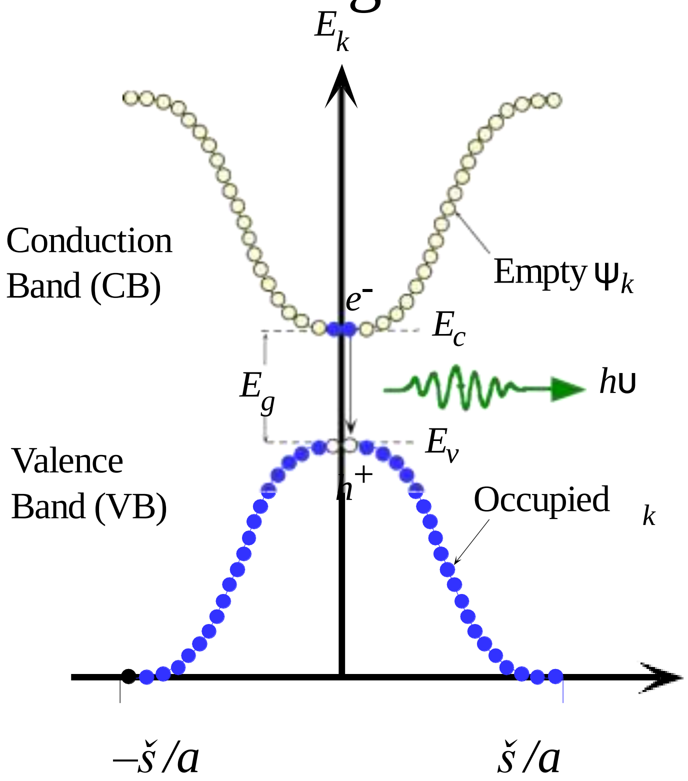
Fiber Optical Sources and Coupling :

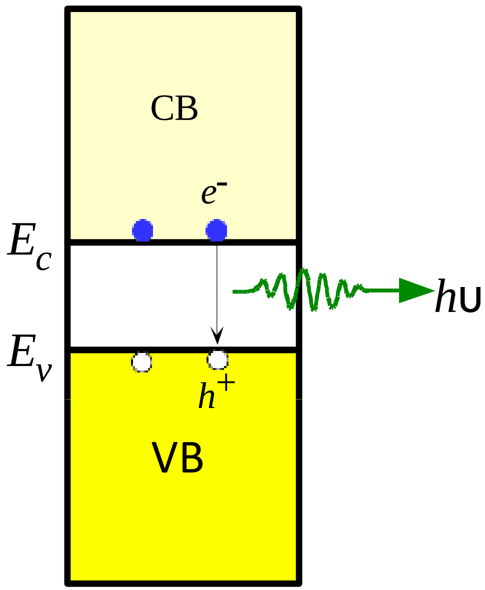
- Direct and indirect Band gap materials
- LED structures
- Light source materials
- Quantum efficiency and LED power,
- Modulation of a LED,
- lasers Diodes
- Modes and Threshold condition
- Rate equations
- External Quantum efficiency

- Resonant frequencies
- Temperature effects

Direct Band Gap Semiconductors

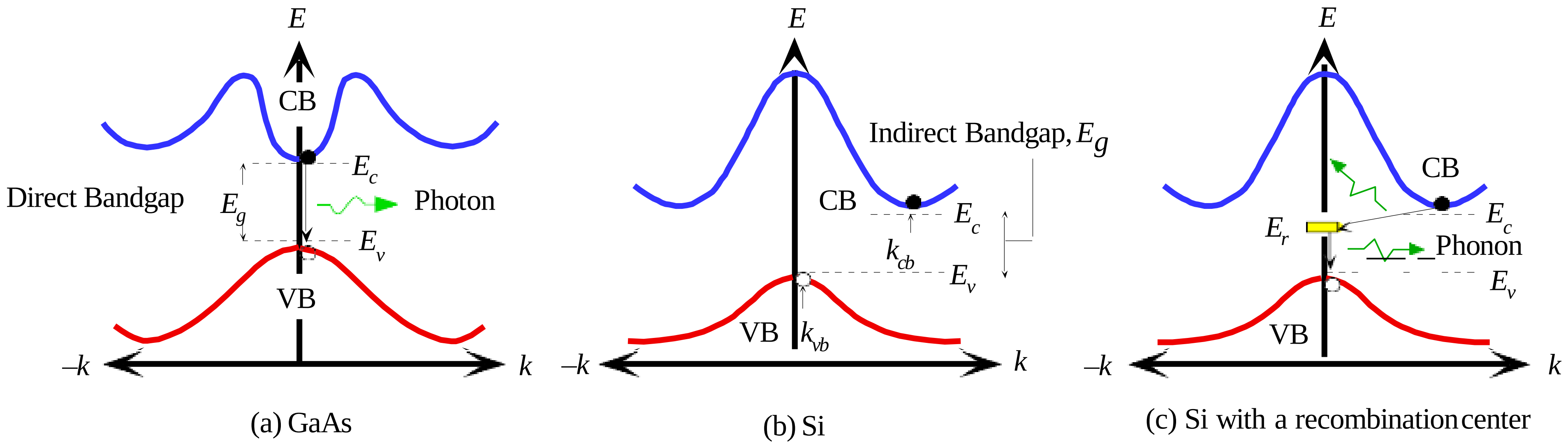
The *E*-*k* Diagram   The Energy Band Diagram



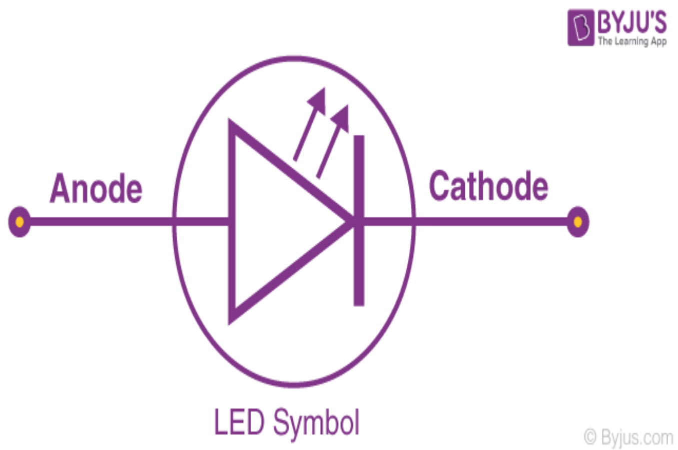


The *E*-*k* diagram of a direct bandgap semiconductor such as GaAs. The *E*-*k* curve consists of many discrete points with each point corresponding to a possible state, wavefunction $\psi_k(x)$, that is allowed to exist in the crystal.

Indirect Band Gap Semiconductors



LED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The Learning App
Anode
Cathode
LED Symbol
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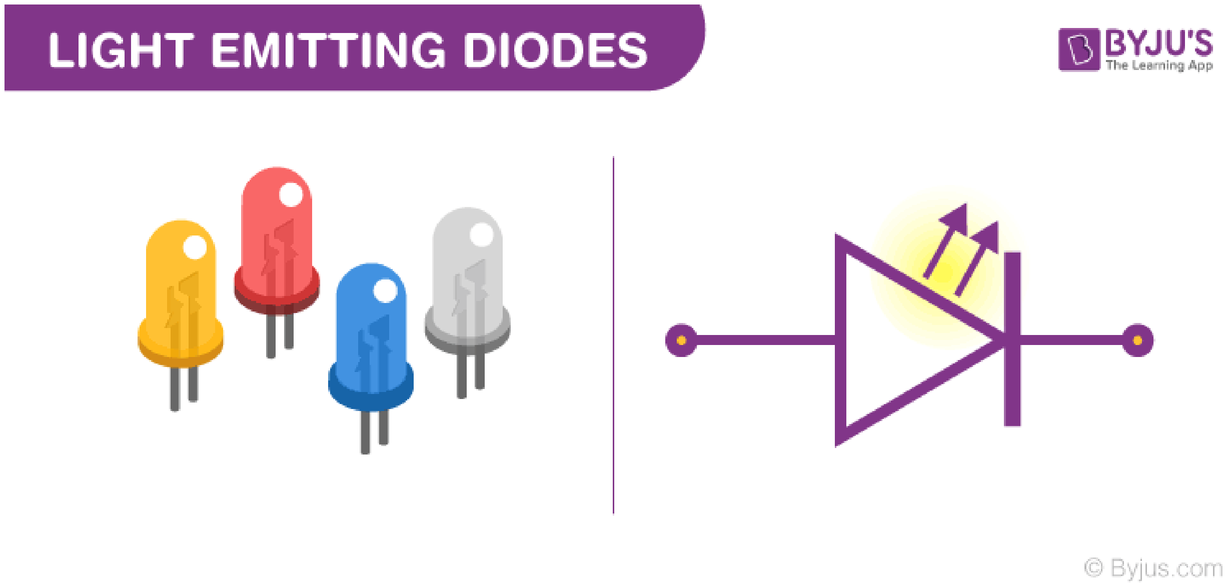
LIGHT EMITTING DIODES
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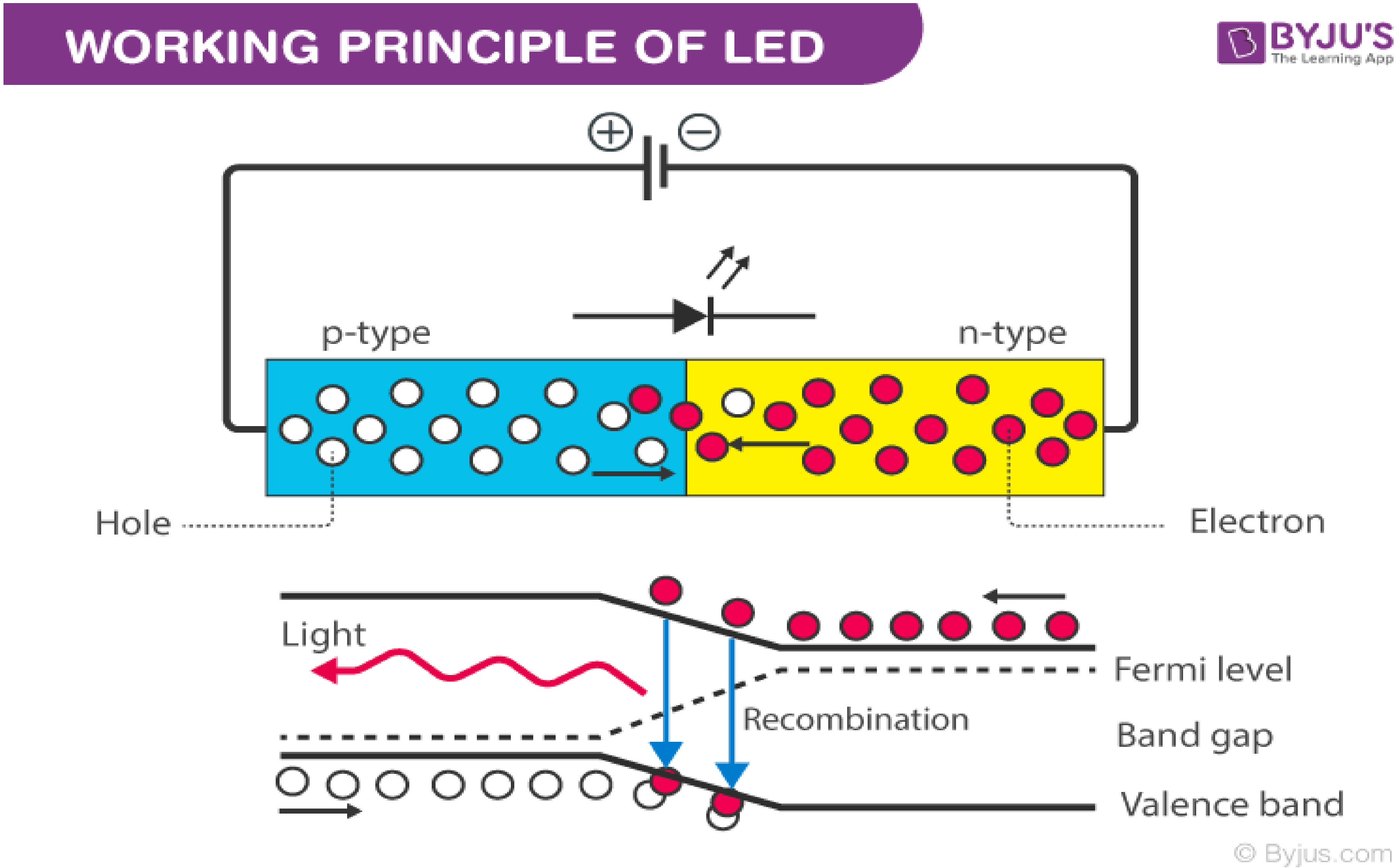
Light-Emitting Diodes (LEDs)

- A light-emitting diode (LED) is a semiconductor device that emits light when an electric current flows through it.
- When current passes through an LED, the electrons recombine with holes emitting light in the process.
- LEDs allow the current to flow in the forward direction and blocks the current in the reverse direction.
- The LED symbol is the standard symbol for a diode, with the addition of two small arrows denoting the emission of light.

……………………CONTINUED

- The two main types of LEDs presently used for lighting systems are aluminum gallium indium phosphide (AlGaInP, sometimes rearranged as AlInGaP) alloys for **red, orange and yellow LEDs; and indium gallium nitride (InGaN) alloys for green, blue and white LEDs**

……………………CONTINUED



WORKING PRINCIPLE OF LED
BYJU'S
The Learning App
p-type
n-type
Hole
Electron
Light
Fermi level
Recombination
Band gap
Valence band
© Byjus.com

LED STRUCTURES

- For photonic communications requiring data rate 100-200 Mb/s with multimode fiber with tens of microwatts, LEDs are usually the best choice.
- LED configurations being used in photonic communications:

  1- Surface Emitters (Front Emitters)

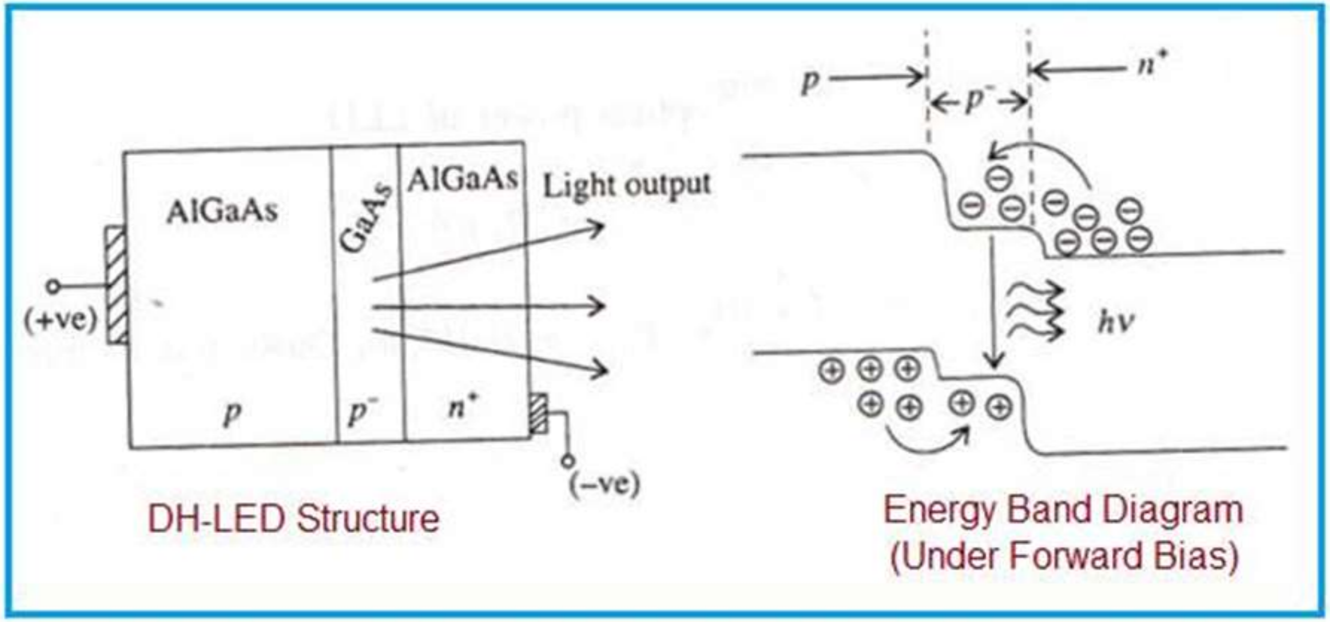
  2- Edge Emitters

Double heterojunction structures

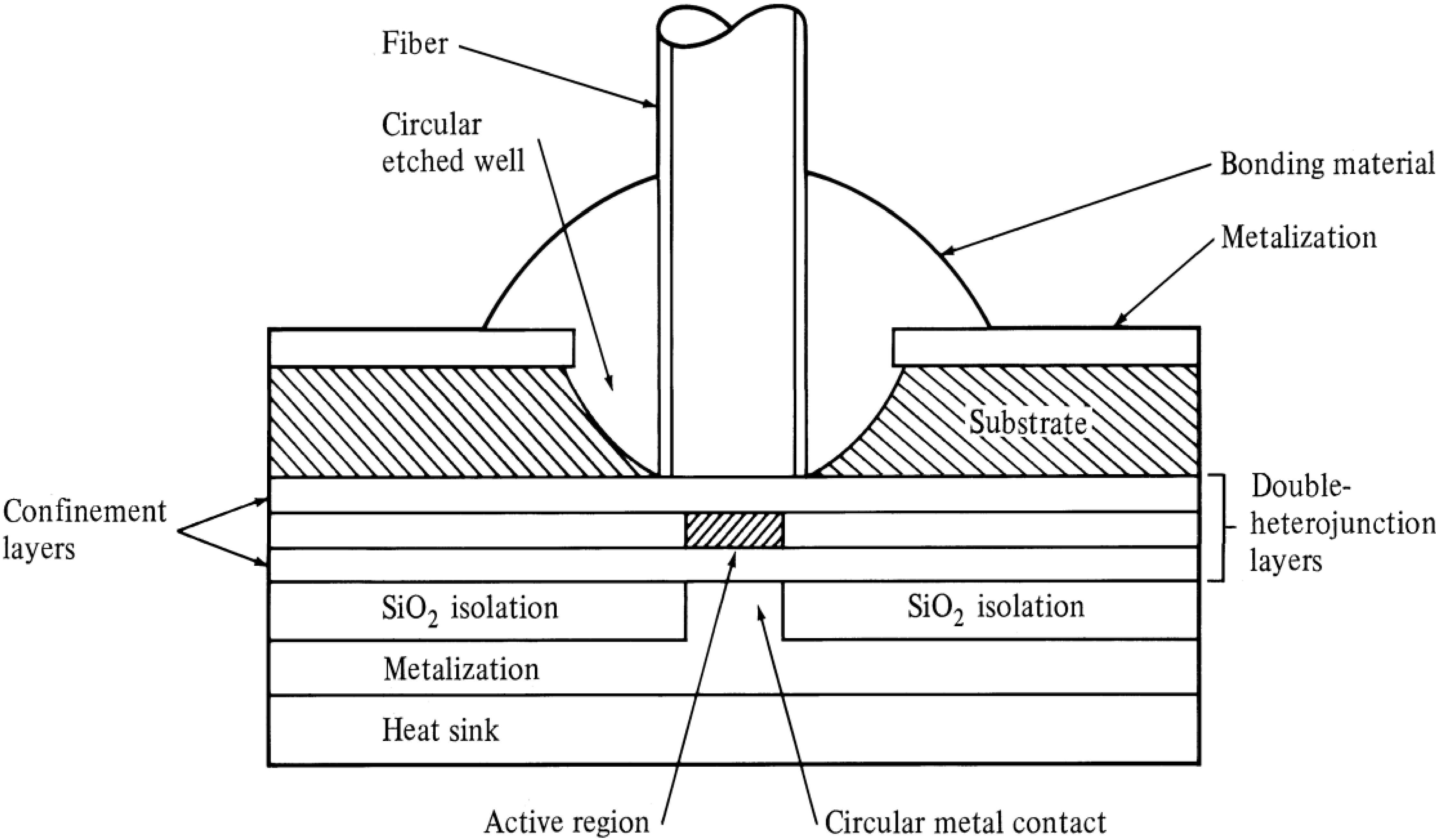
- As shown it is GaAs/AlGaAs based **Double Heterojunction LED**.
- As shown thin layer of GaAs is sandwiched between two layers of AlGaAs. GaAs is lightly doped and has narrower bandgap (Eg1) of about 1.43 eV. AlGaAs layers have wider bandgap (Eg2) of about 2.1 eV.
- When forward bias is applied through its top and bottom contacts as shown in the figure, electrons are injected from highly doped (n^+) AlGaAs layer to central active (p^-) GaAs layer.

  • The injected electrons are trapped within the middle layer due to double heterojunction potential barriers (Eg2 > Eg1) existing on both the sides of the middle layer.

- The figure depicts energy band diagram when it is forward biased. Electrons are forced to recombine with the holes without too much diffusion from interfaces.
- They recombine radiatively with energy equal to the band gap of GaAs.
- As recombination between electrons and holes is limited to narrower central part, internal quantum efficiency of such LED is higher compare to single junction LED.



Surface-Emitting LED



Benefits or advantages of Surface Emitting LED

➡LED offers high optical coupling efficiency.

➡Optical loss (due to internal absorption) is very low. This is because of carrier recombination near its top heterojunction.

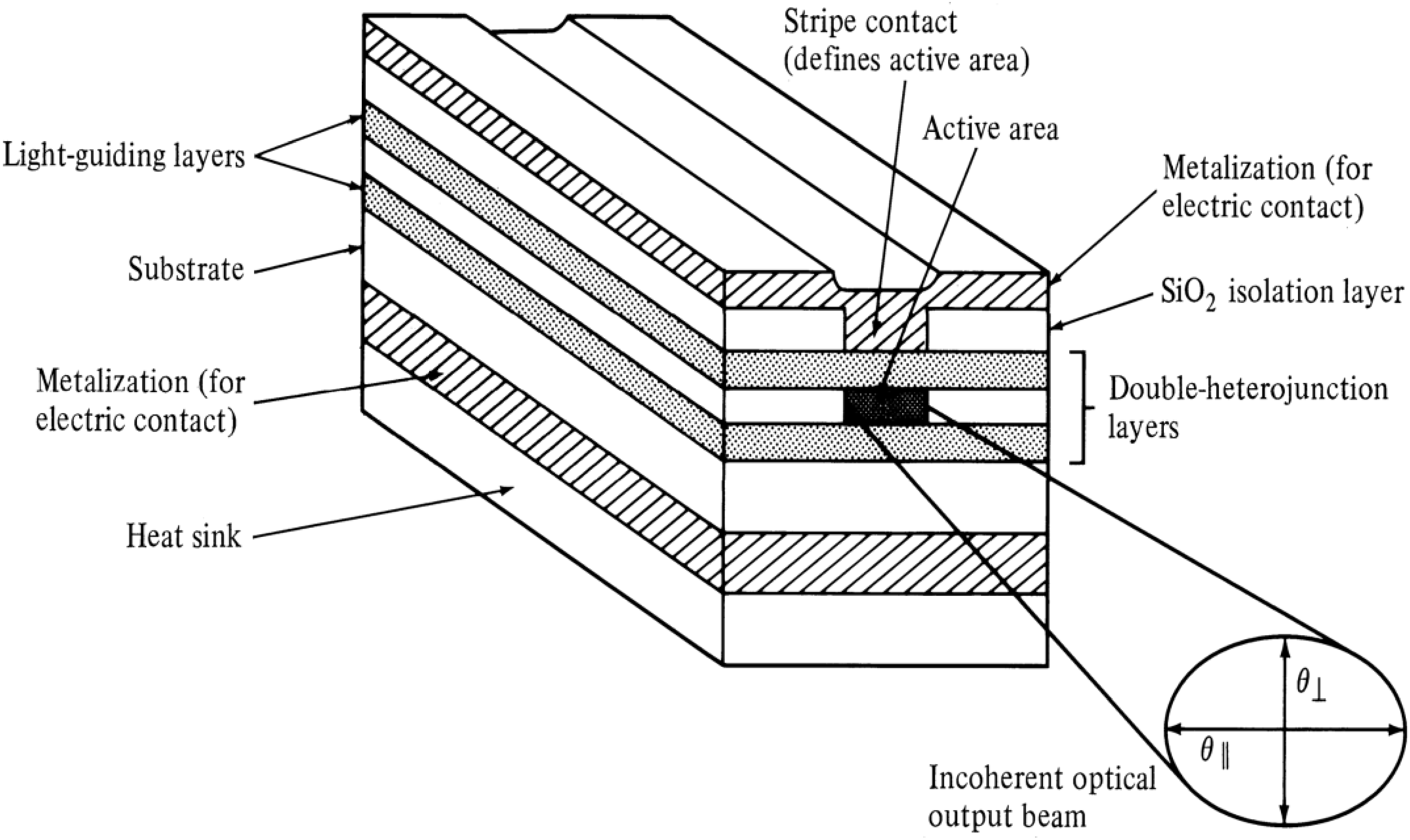
➡InP/InGaAsP based LED is used for long wavelength applications.

➡It offers higher efficiency with low to high radiance.

Drawbacks ➡The surface emitting LED can transmit data rate less than 20 Mbps than edge emitting LED.

➡It contains short optical link with large NA (Numerical Aperture).

Edge-Emitting LED



Benefits or advantages ➡It offers higher efficiency with low to high radiance. ➡It offers better modulation bandwidth and more directional emission pattern.

➡It offers 5-6 times more coupled power into NA (Numerical Aperture) of step/graded index fibers. This is due to small beam divergence.

➡It offers high data rates (> 20 Mbps) than surface emitting LED.

Drawbacks ➡Its structure is complex.

➡It is difficult to design heat sink.

➡It is expensive compare to other LED types.

➡There are many issues to be handled during mechanical mounting and installation.

Light Source Materials

active region material of an optical source must have direct band gap.

In direct band gap materials,radiative recombination is sufficiently high to produce adequete optical emission.

These materials are compound of group III elements(Al, Ga or In) and of group IV elements(P,As).

These materials determine the wave length of light emitted.

Quantum Efficiency & LED power

- When there is no external carrier injection, the excess density decays exponentially due to electron-hole recombination.

$$n(t) = n_0 e^{-t/\tau}$$

n_0 : initial injected excess electron density

τ: carrier lifetime.

- Bulk recombination rate R:

$$R = -\frac{dn}{dt} = \frac{n}{\tau}$$

- Bulk recombination rate (R)=Radiative recombination rate + nonradiative recombination rate

  - n is the excess carrier density,

Internal Quantum Efficiency & Optical Power

η_{int}: internal quantum efficiency in the active region

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}} = \frac{\tau_{nr}}{\tau_r + \tau_{nr}} = \frac{\tau}{\tau_r}$$

Optical power generated internally in the active region in the LED is:

$$P_{int} = \eta_{int} \frac{I}{q} h\nu = \eta_{int} \frac{hcI}{q\lambda}$$

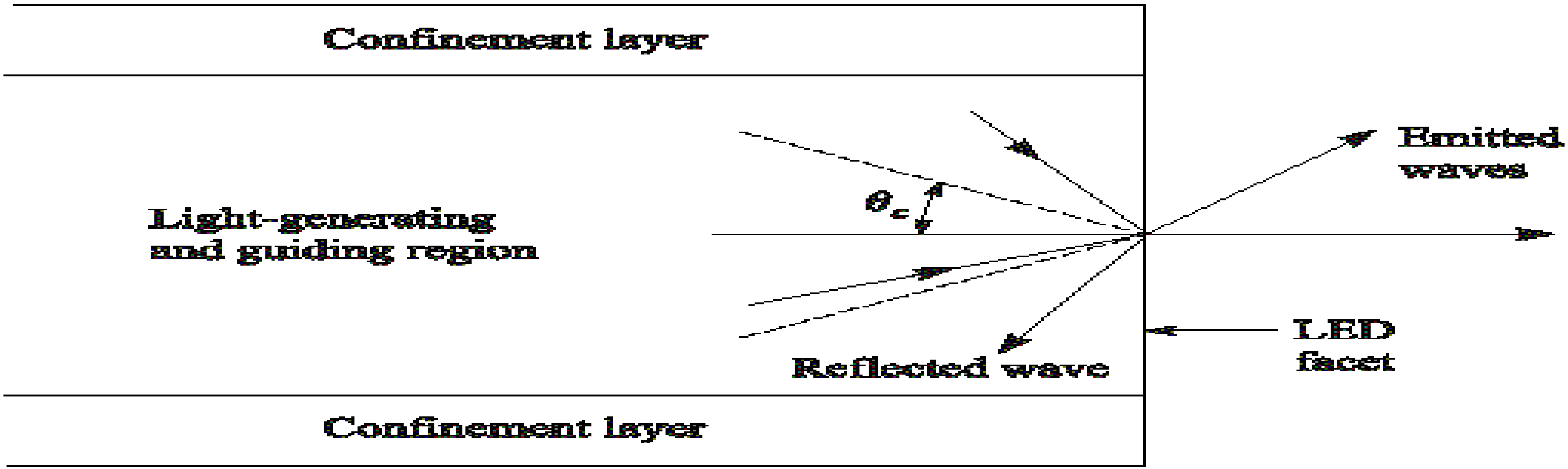
P_{int} : Internal optical power,

I : Injected current to active region

External Quantum Eficiency

$$\eta_{ext} = \frac{\text{No.of photons emitted from LED}}{\text{No.of LED internally generated photons}}$$

- In order to calculate the external quantum efficiency, we need to consider the reflection effects at the surface of the LED. If we consider the LED structure as a simple 2D slab waveguide, only light falling within a cone defined by critical angle will be emitted from an LED.



$$\eta_{ext} = \frac{1}{4\pi}\int_0^{\varphi_c} T(\varphi)(2\pi\sin\varphi)\,d\varphi$$

$T(\varphi)$: Fresnel Transmission Coefficient $\approx T(0) = \dfrac{4n_1n_2}{(n_1+n_2)^2}$

If $n_2 = 1 \Rightarrow \eta_{ext} \approx \dfrac{1}{n_1(n_1+1)^2}$

LED emitted optical power, $P = \eta_{ext} P_{int} \approx \dfrac{P_{int}}{n_1(n_1+1)^2}$

Modulation of LED

- The frequency response of an LED depends on:

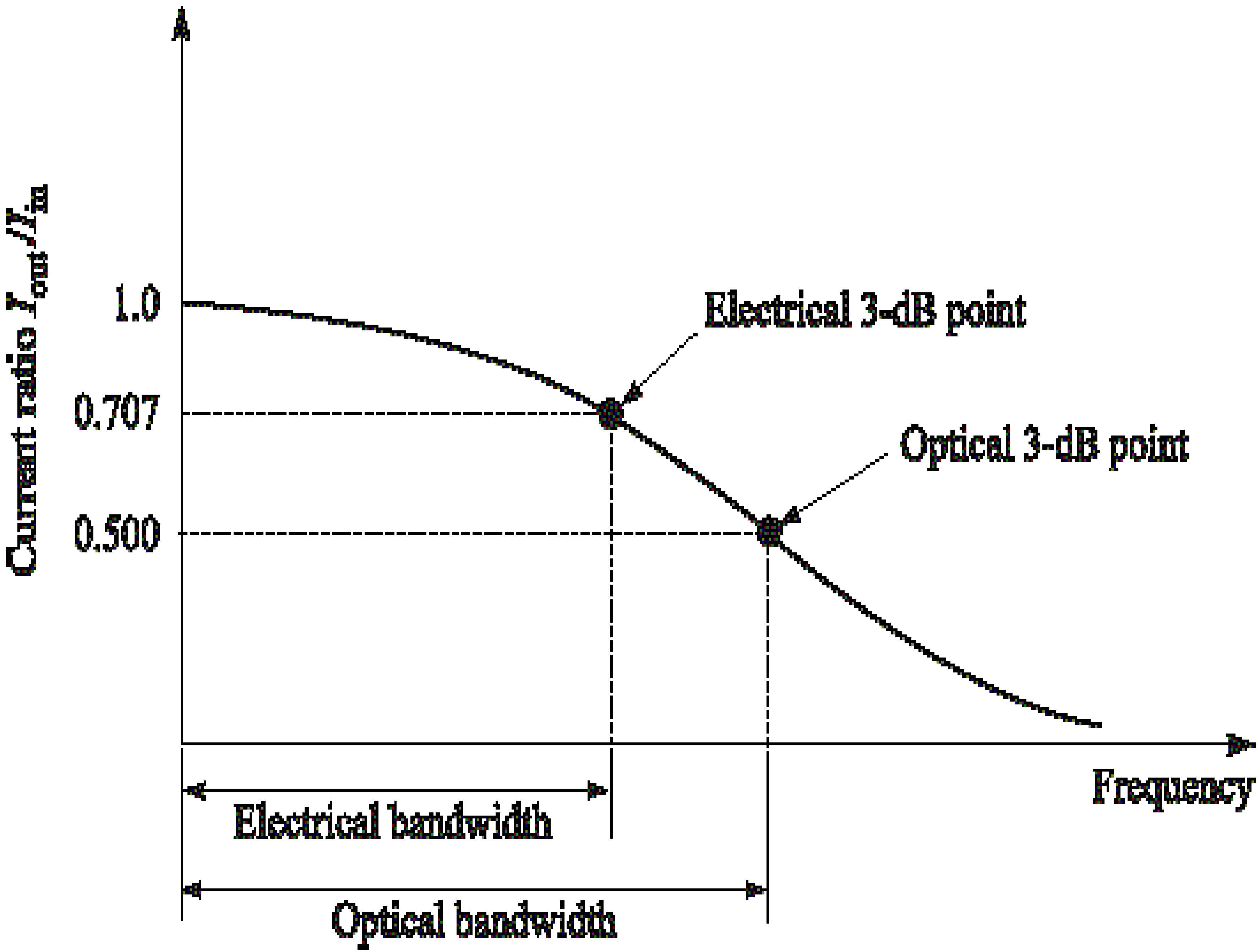
  1- Doping level in the active region

  2- Injected carrier lifetime in the recombination region, τ .

  3- Parasitic capacitance of the LED

- If the drive current of an LED is modulated at a frequency of ω the output optical power of the device will vary as:

$$P(\omega) = \frac{P_0}{\sqrt{1+(\omega\tau_i)^2}}$$



Current ratio I_{out}/I_{in}
1.0
0.707
0.500
Electrical 3-dB point
Optical 3-dB point
Frequency
Electrical bandwidth
Optical bandwidth

Advantages

- LEDs consume less power, and they require low operational voltage
- The emitted light is monochromatic.
- In expensive
- Reliable
- Easy to handle
- Less temparature dependance

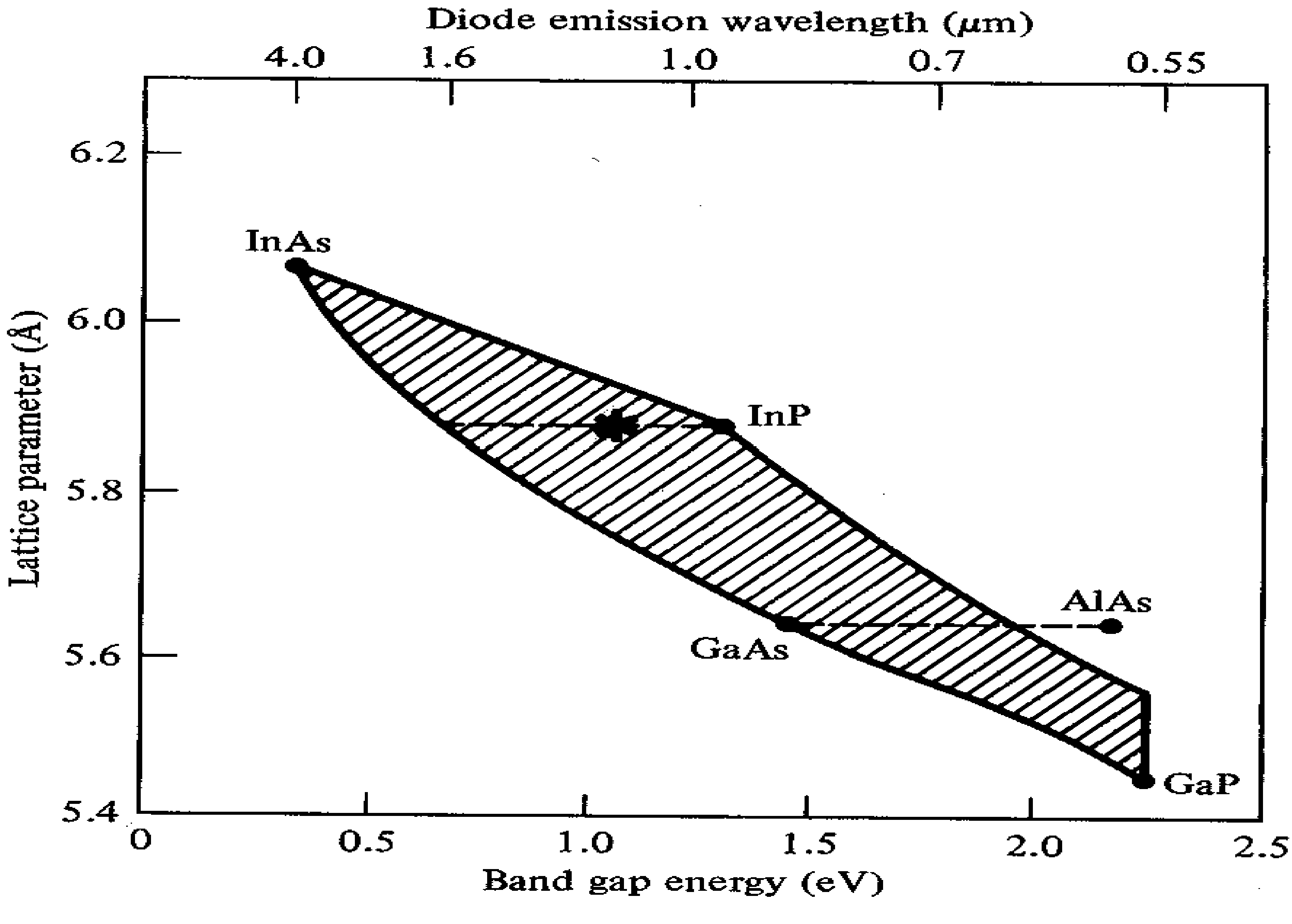
Dis advantages

- Low output power
- Short distance communication
- More harmonic distortion

APLLICATIONS

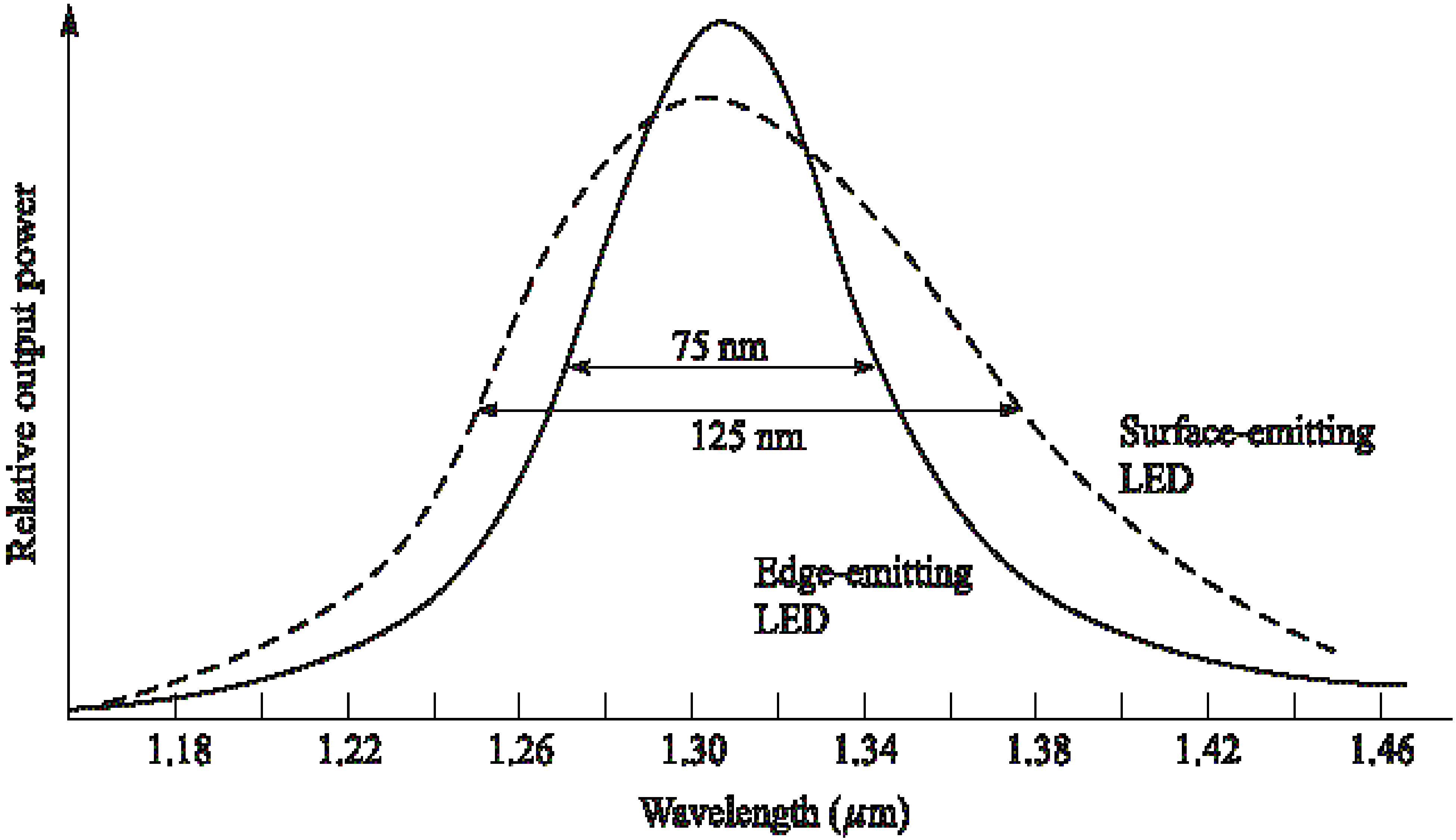
- Leds are used at 850nm and 13510 nm
- Lan & wan
- CCTV
- Used for TV back-lighting
- Used in displays
- Used in Automotives
- LEDs used in the dimming of lights

Semiconductor material	Band gap energy (eV)	Wavelength (μm)
InP	1.35	0.92
InAs	0.34	3.6
GaP	2.24	0.55
GaAs	1.42	0.87
AlAs	2.09	0.59
GaInP	1.82-1.94	0.64-0.68
AlGaAs	1.4-1.55	0.8-0.9
InGaAs	0.95-1.24	1.0-1.3
InGaAsP	0.73-1.35	0.9-1.7



Diode emission wavelength (μm)
4.0
1.6
1.0
0.7
0.55
6.2
6.0
5.8
5.6
5.4
Lattice parameter (Å)
InAs
InP
AlAs
GaAs
GaP
0
0.5
1.0
1.5
2.0
2.5
Band gap energy (eV)

Spectral width of LED types



LASER

- LASER means light amplification by stimulated emission of radiation.
- It is widely used optical source for optical communication.
- It is working on the principle of stimulated emission.
- It has coherent light.
- Laser diode suffers from 3 problems when used as optical source :
- Temperature sensitivity
- Back reflections
- Susceptible to optical interference

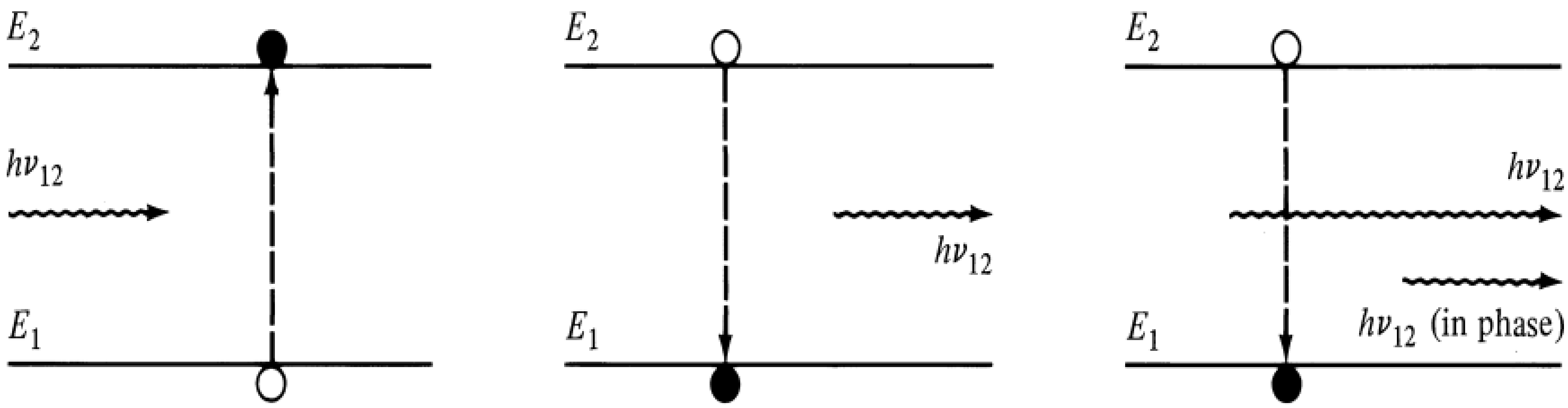
Pumped active medium

- Three main process for laser action:

  1- Photon absorption

  2 Spontaneous emission

  3 Stimulated emission



(a) Absorption (b) Spontaneous emission (c) Stimulated emission

Energy absorbed from the incoming photon

Random release of energy

Coherent release of energy

Lasing in a pumped active medium

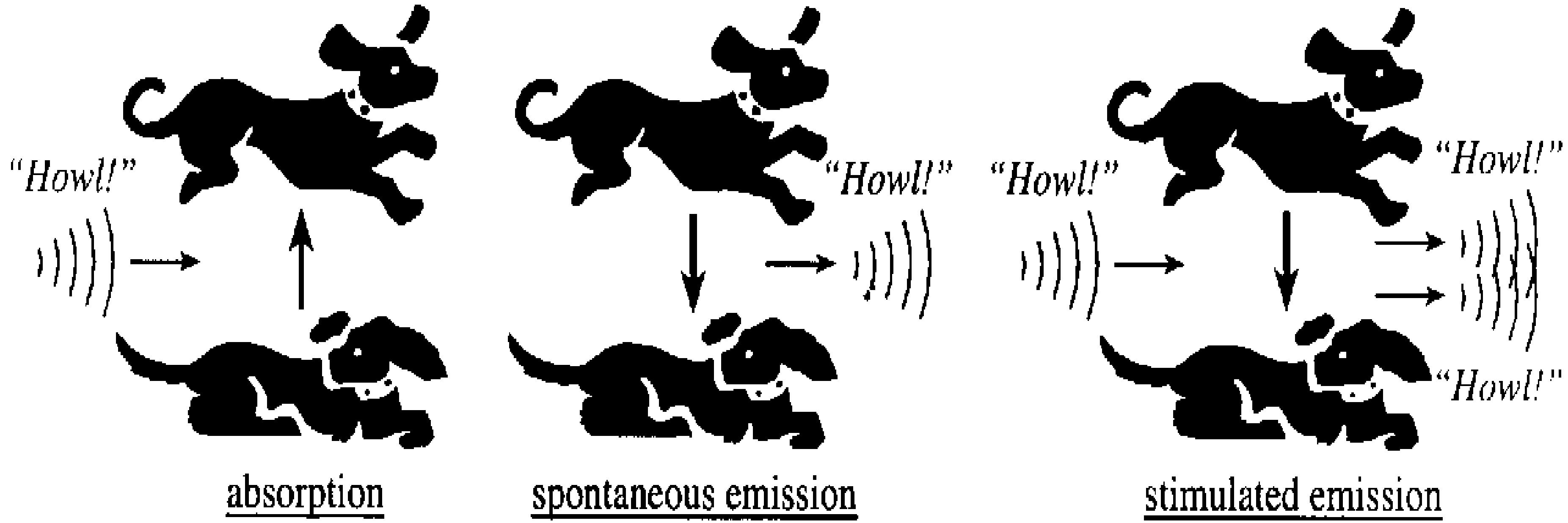
- In thermal equilibrium the stimulated emission is essentially negligible, since the density of electrons in the excited state is very small, and optical emission is mainly because of the spontaneous emission. Stimulated emission will exceed absorption only if the population of the excited states is greater than that of the ground state. This condition is known as **Population Inversion**. Population inversion is achieved by various **pumping** techniques.

Howling Dog Analogy

1. absorption: a dog in the ground state might hear the howl from another dog and become excited, thus making a transition to the excited state.

2. spontaneous emission: a dog in the excited state might randomly let out a howl, which, through release of tension, enables him to relax to the ground state.

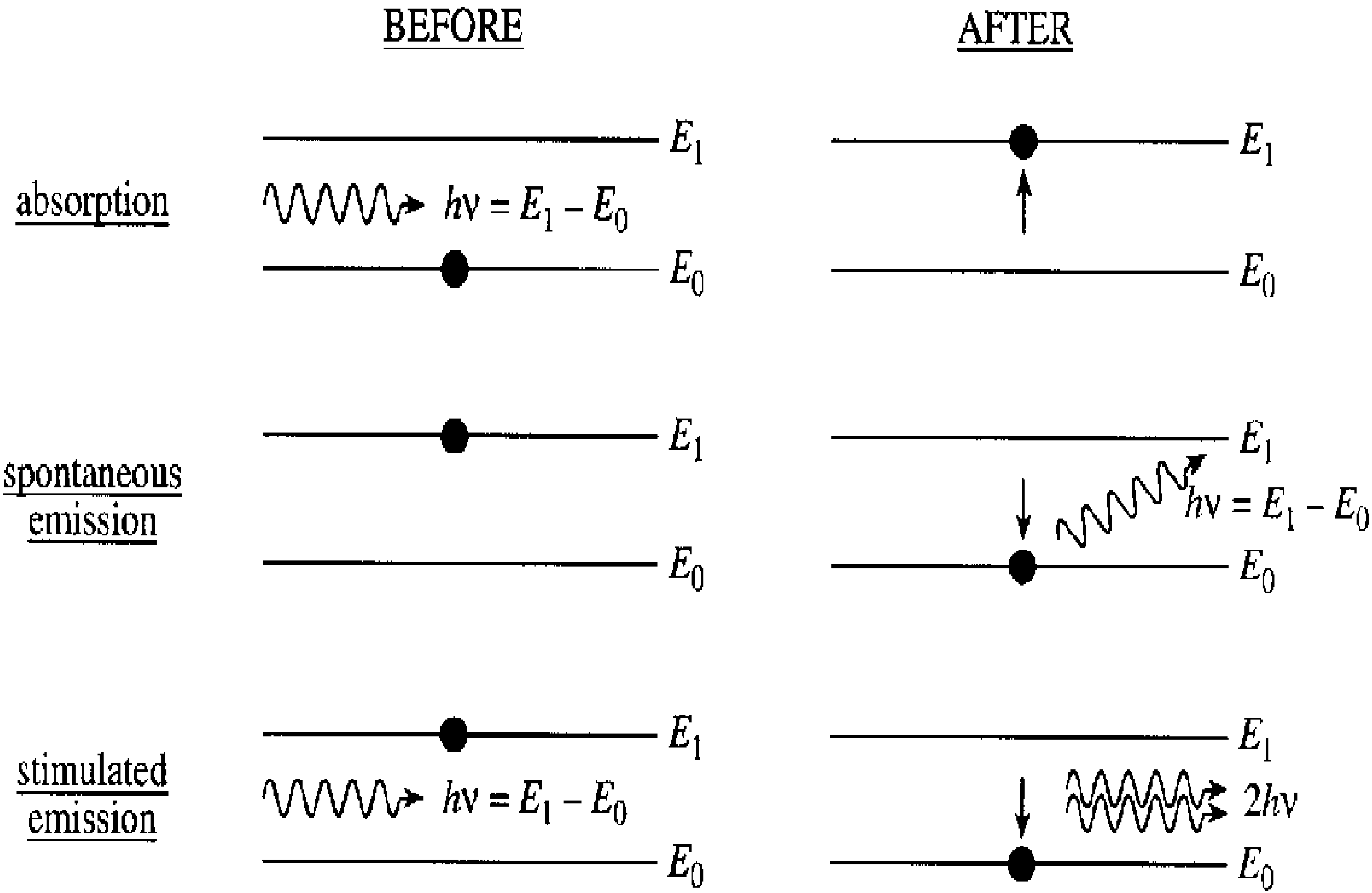
3. stimulated emission: a dog in the excited state might be stimulated to let out a howl when he hears the howl from another dog. The single howl becomes two howls voiced simultaneously, thus sounding like one howl with twice the intensity!

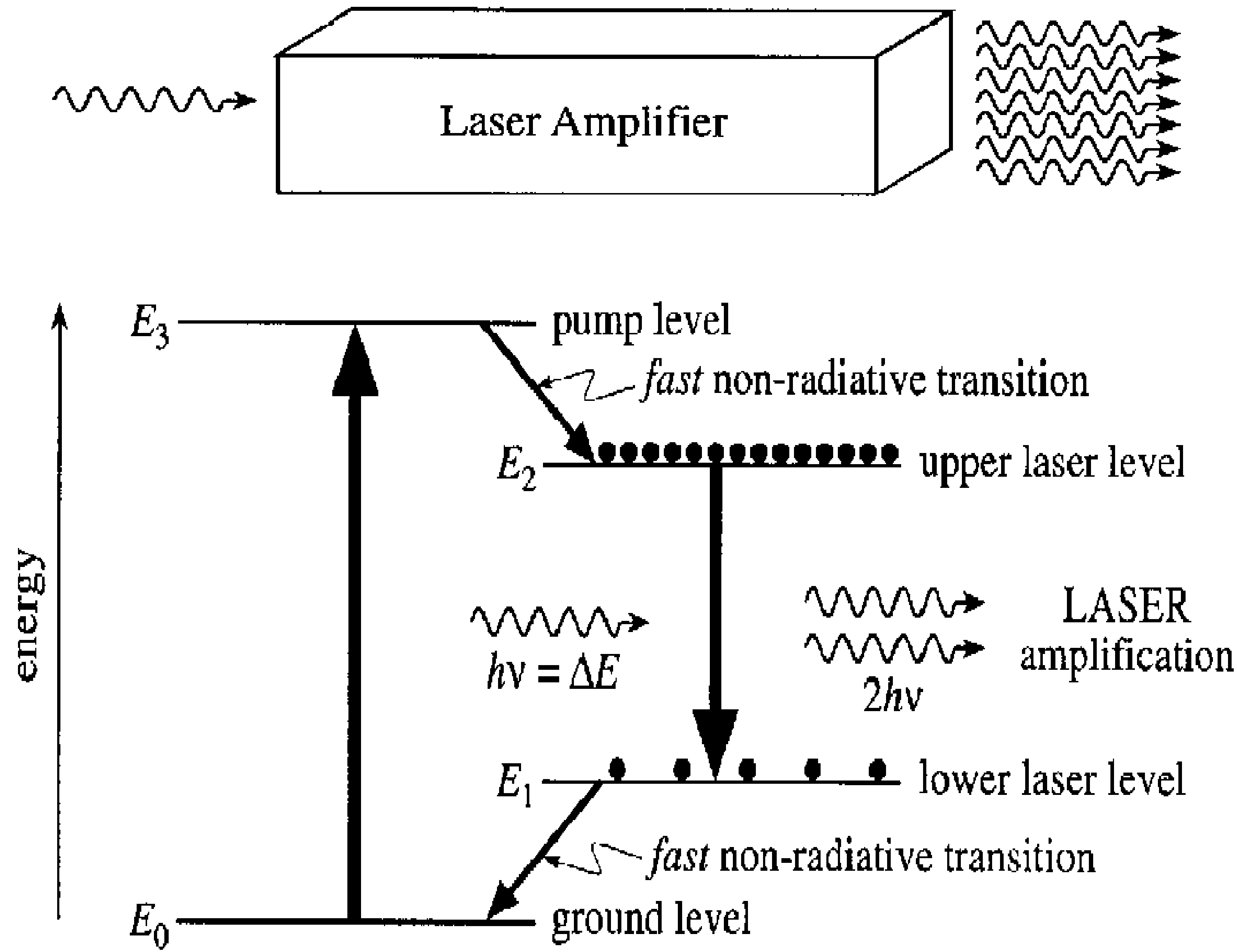


In Stimulated Emission incident and stimulated photons will have

- Identical energy € Identical wavelength € Narrow linewidth
- Identical direction € Narrow beam width
- Identical phase € Coherence and
- Identical polarization

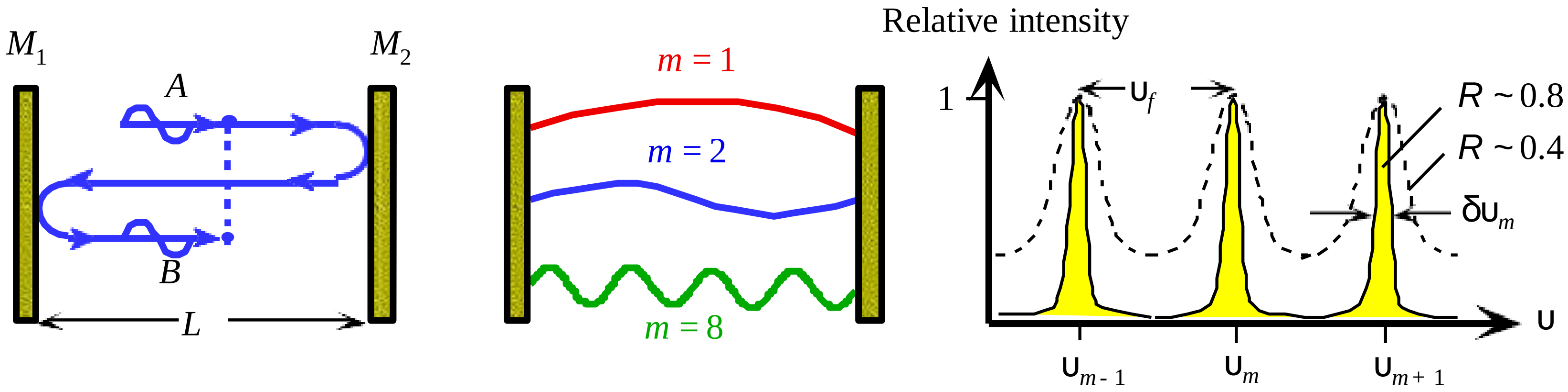
Stimulated Emission





Laser Amplifier
energy
E_3
pump level
fast non-radiative transition
E_2
upper laser level
$h\nu = \Delta E$
LASER
amplification
$2h\nu$
E_1
lower laser level
fast non-radiative transition
E_0
ground level

Fabry-Perot Resonator



(a) (b) (c)

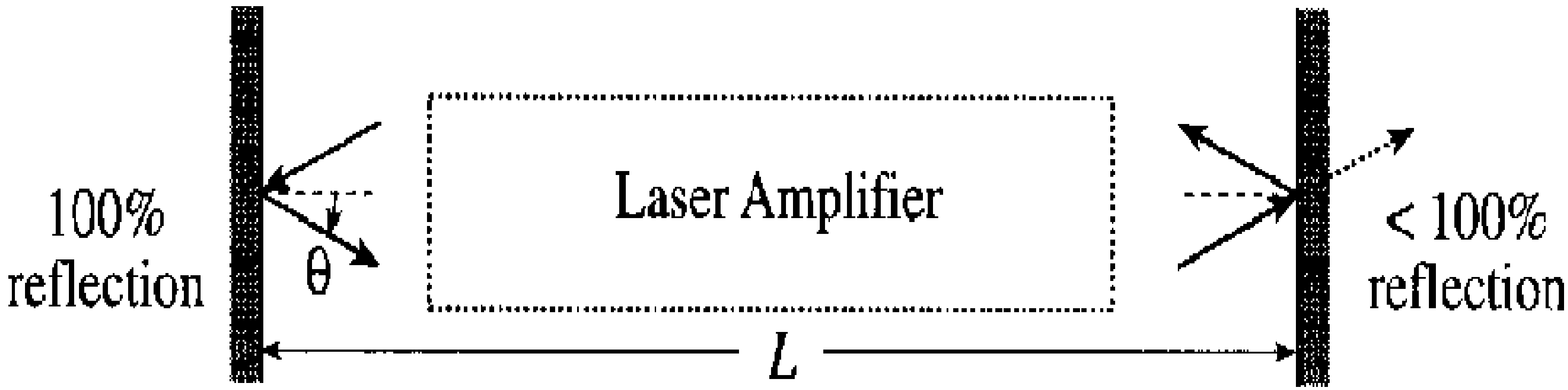
$$\text{Resonant modes}: kL = m\pi \qquad m = 1,2,3,..$$

Schematic illustration of the Fabry-Perot optical cavity and its properties. (a) Reflected waves interfere. (b) Only standing EM waves, *modes*, of certain wavelengths are allowed in the cavity. (c) Intensity vs. frequency for various modes. R is mirror reflectance and lower R means higher loss from the cavity.

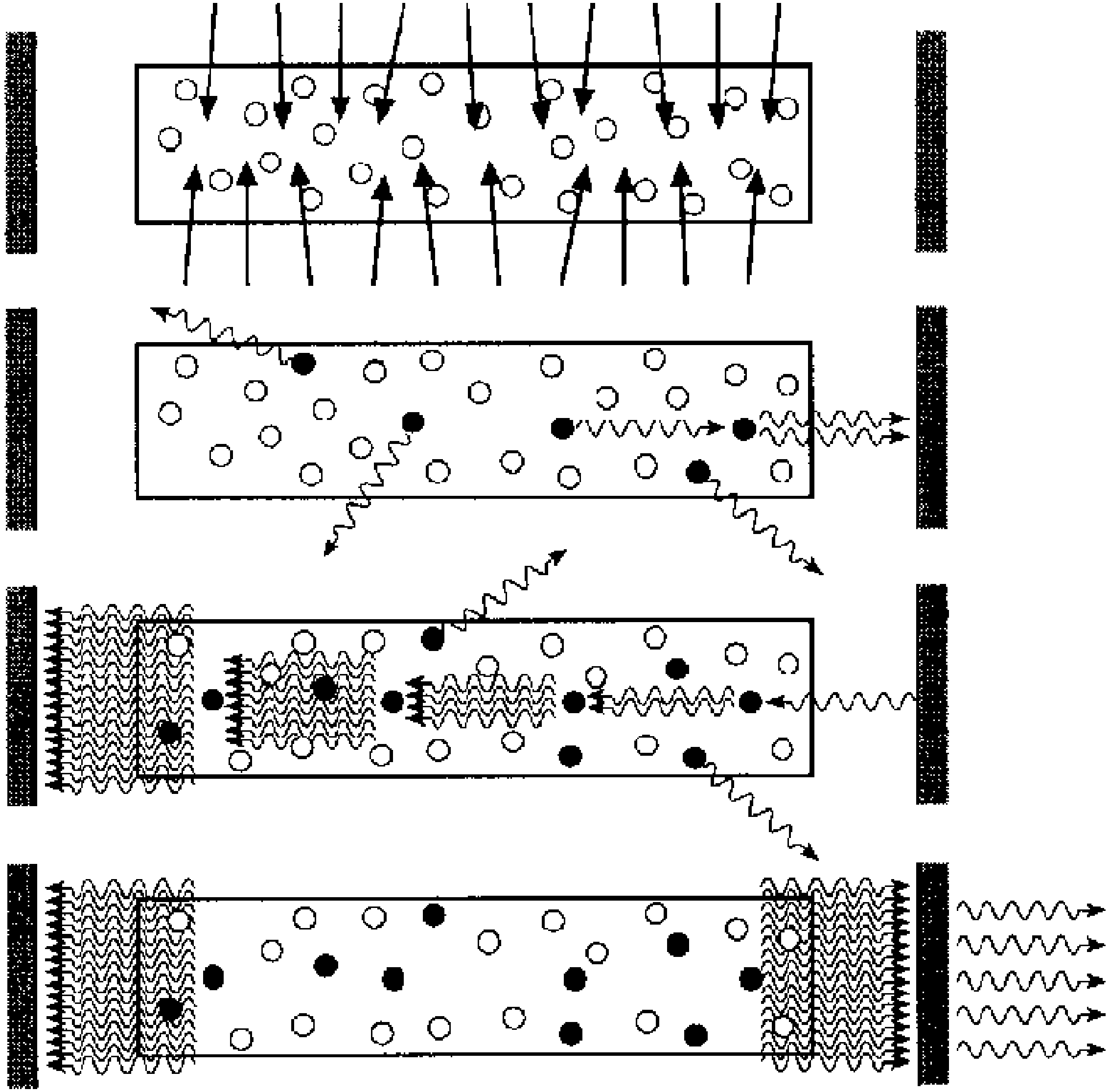
$$I_{trans} = I_{inc} \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(kL)} \qquad [4\text{-}18]$$

R: reflectance of the optical intensity, *k*: optical wavenumber

Mirror Reflections



How a Laser Works



pump on
○ = atoms in excited state

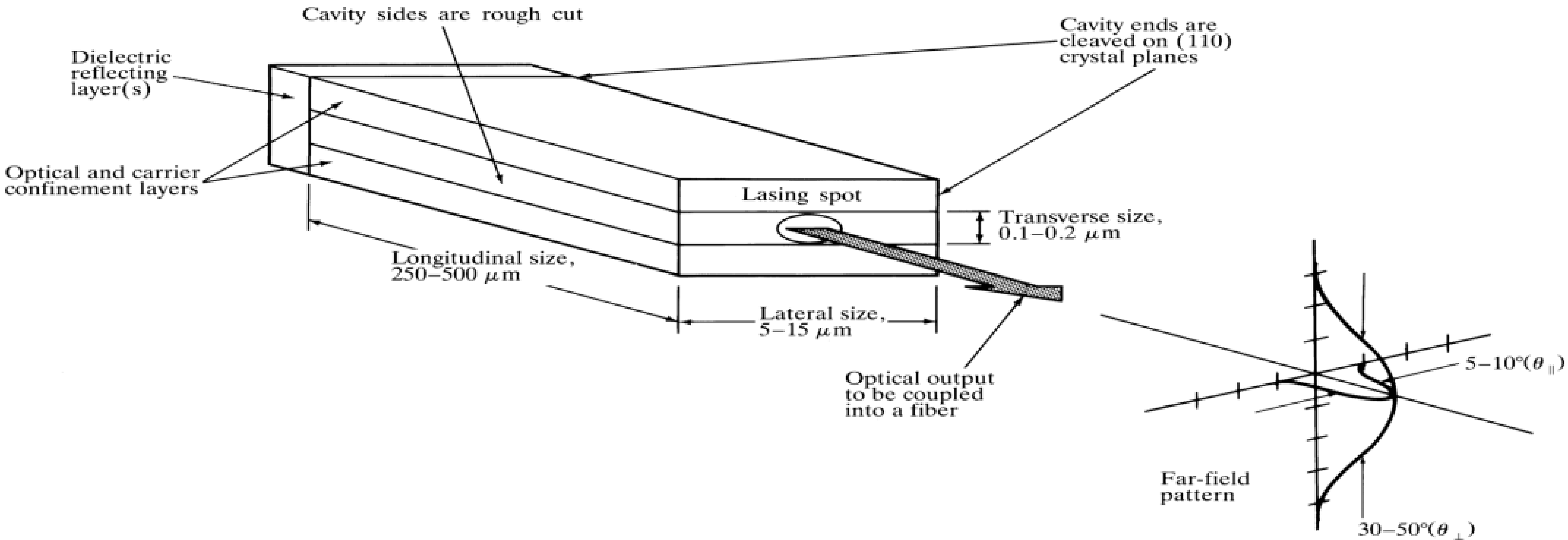
spontaneous emission &
rare stimulated emission

stimulated emission of
light along the laser axis

steady-state
laser operation

Laser Diode

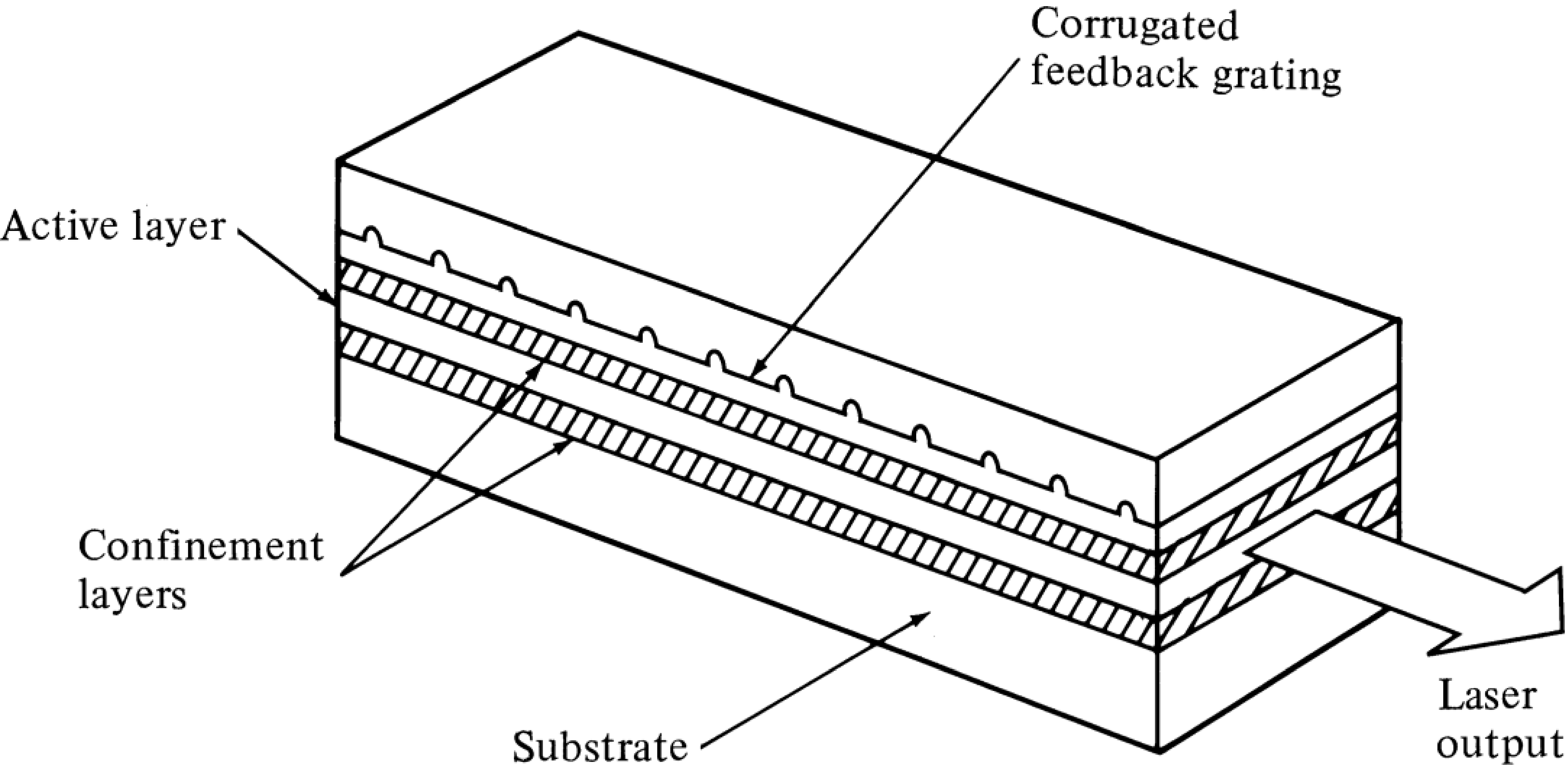
- Laser diode is an improved LED, in the sense that uses stimulated emission in semiconductor from optical transitions between distribution energy states of the valence and conduction bands with optical resonator structure such as Fabry-Perot resonator with both optical and carrier confinements.



Laser Diode Modes

- Nanosecond & even picosecond response time (GHz BW)
- Spectral width of the order of nm or less
- High output power (tens of mW)
- Narrow beam (good coupling to single mode fibers)
- Laser diodes have three distinct radiation modes namely, longitudinal, lateral and transverse modes.
- In laser diodes, end mirrors provide strong optical feedback in longitudinal direction, so by roughening the edges and cleaving the facets, the radiation can be achieved in longitudinal direction rather than lateral direction.

DFB(Distributed FeedBack) Lasers



The optical feedback is provided by fiber Bragg Gratings € Only one wavelength get positive feedback

Threshold Condition

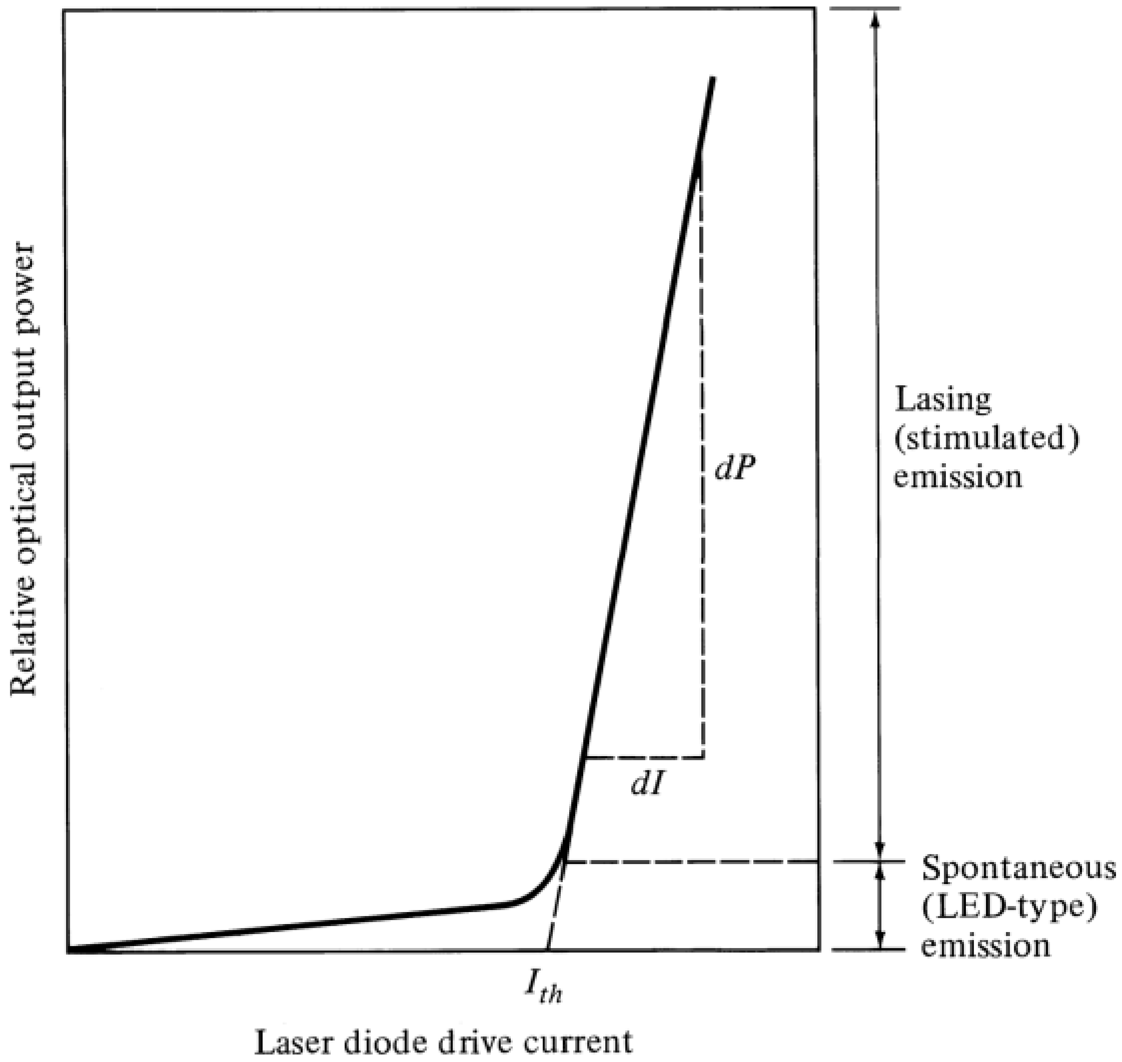
- To determine the lasing condition and resonant frequencies, we should focus on the optical wave propagation along the longitudinal direction, *z*-axis. The optical field intensity, *I*, can be written as:

$$I(z,t) = I(z)e^{j(\omega t - \beta z)}$$

- Lasing is the condition at which light amplification becomes possible by virtue of population inversion. Then, stimulated emission rate into a given EM mode is proportional to the intensity of the optical radiation in that mode.

$$g_{th} = \beta J_{th}$$

Optical output vs. drive current



Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Rate equations

Rate equations relate the optical output power, or # of photons per unit volume, Φ, to the diode drive current or # of injected electrons per unit volume, *n*. For active (carrier confinement) region of depth *d*, the rate equations are:

$$\frac{d\Phi}{dt} = Cn\Phi + R_{sp} - \frac{\Phi}{\tau_{ph}} \qquad [4\text{-}25]$$

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\Phi$$

Photon rate = stimulated emission + spontaneou s emission + photon loss

Threshold current Density & excess electron density

- At the threshold of lasing: $\Phi \approx 0,\ d\Phi/dt \geq 0,\ R_{sp} \approx 0$

$$\text{from eq.}[4-25] \Rightarrow Cn\Phi - \Phi/\tau_{ph} \geq 0 \Rightarrow n \geq \boxed{\frac{1}{C\tau_{ph}} = n_{th}}$$ [4-26]

- The threshold current needed to maintain a steady state threshold concentration of the excess electron, is found from electron rate equation under steady state condition *dn/dt=0* when the laser is just about to lase:

$$0 = \frac{J_{th}}{qd} - \frac{n_{th}}{\tau_{sp}} \Rightarrow \boxed{J_{th} = qd\frac{n_{th}}{\tau_{sp}}}$$ [4-27]

Laser operation beyond the threshold

$J > J_{th}$

- the steady state photon density, resulting from stimulated emission and spontaneous emission as follows:

$$\Phi_s = \frac{\tau_{ph}}{qd}(J - J_{th}) + \tau_{ph} R_{sp}$$

External quantum efficiency

- Number of photons emitted per radiative electron-hole pair recombination above threshold, gives us the external quantum efficiency.

$$\eta_{ext} = \frac{\eta_i (g_{th} - \alpha)}{g_{th}}$$

[4-29]

Resonant Frequencies

- Lasing condition:

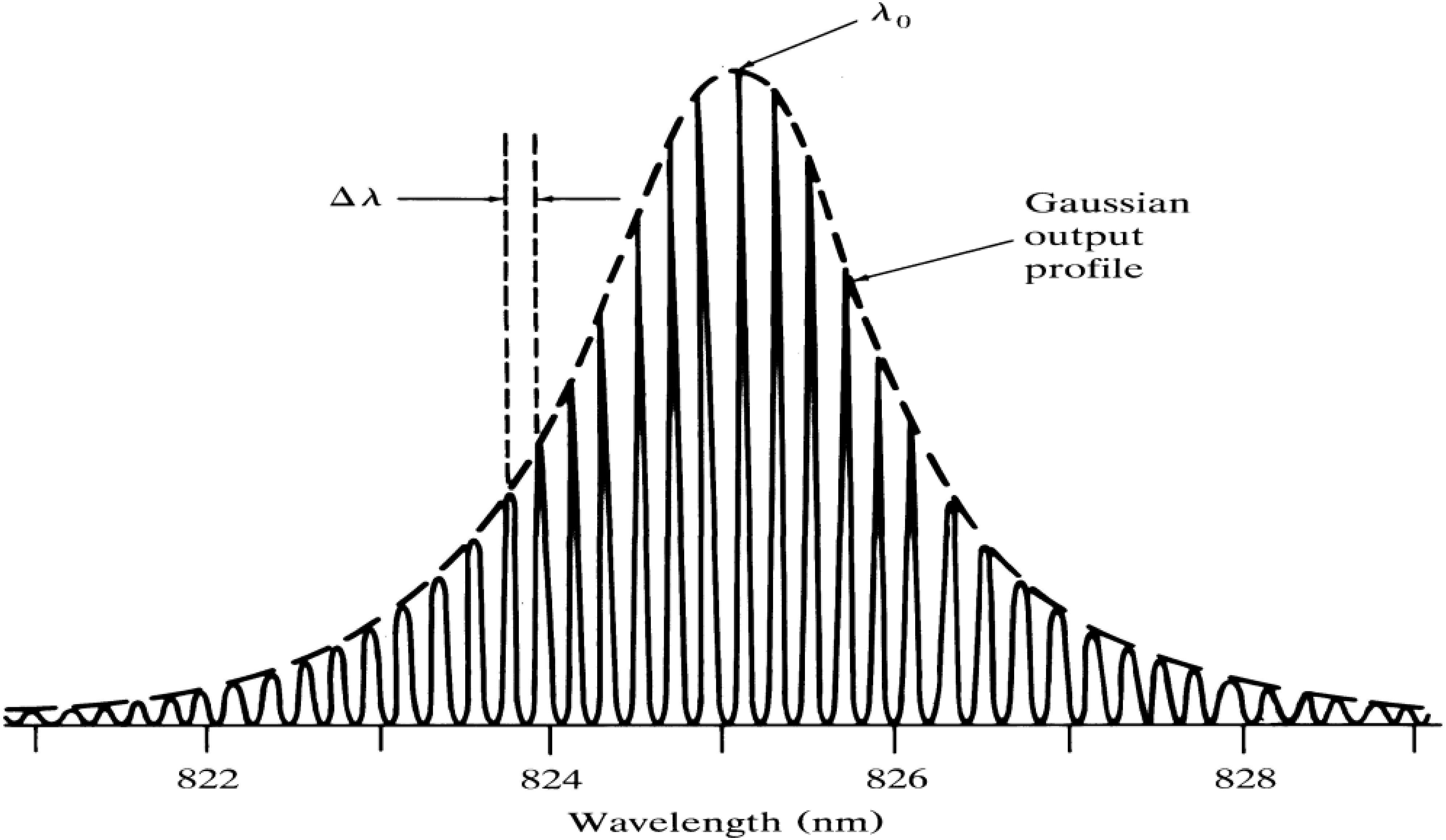
$$\exp(-j2\beta L) = 1 \Rightarrow \qquad 2\beta L = 2m\pi, \qquad m = 1,2,3,\ldots$$

- Assuming $\beta = \frac{2\pi n}{\lambda}$ the resonant frequency of the *m*th mode is:

$$\nu_m = \frac{mc}{2Ln} \qquad m = 1,2,3,\ldots \qquad [4\text{-}30]$$

$$\Delta\nu = \nu_m - \nu_{m-1} = \frac{c}{2Ln} \Leftrightarrow \Delta\lambda = \frac{\lambda^2}{2Ln} \qquad [4\text{-}31]$$

Spectrum from a Laser Diode



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- FibertoFiberJointLosses TypesofFibertoFiberJointLosses #Lossesduetodifferenceindiameter

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Department of Electronics and Communication Engineering

OPTICAL FIBER COMMUNICATION

UNIT-III

FIBER OPTICAL RECEIVERS

contents

- PIN and APD diodes
- Photo detector noise
- SNR
- Detector response time
- Avalanche Multiplication noise
- Comparison of photo detectors
- Fundamental Receiver Operation
- Preamplifiers
- Error sources
- Receiver configuration

Photo Detectors

- Optical detectors convert optical signal (light) to electrical signal (current/voltage)
  - Hence referred ‘O/E Converter’
- Photodetector is the fundamental element of optical receiver, followed by amplifiers and signal conditioning circuitry
- There are several photodetector types:
  - Photodiodes, Phototransistors, Photon multipliers, Photo-resistors etc.

requirements of photo detectors

- Compatible *Physical Dimensions (small size)*
- High *Response or Selectivity* at desired wavelength.
- Low *Noise* added to the system and high *Gain*
- High *Bandwidth* → Fast response time
- Stable performance
- Long Operating *Life* and low *Cost*

Principle of photo detector

- Working principle is optical absorption
- The main purpose ofis its fast reponse
- For foc most suited photo detectors are PIN(P type intrinsic N type) and (Avalancha photo diode)

Performance of photodetector

- Quantum efficiency: ratio of no of electron-hole carrier generated to no of incident photons
- Responsivity:output current to incident optical power
- Wavelength
- Dark current: electrical current under total darkness condituon.

Photodiodes

- *Photodiodes* meet most of the requirements, hence widely used as photo detectors.
- Positive-Intrinsic-Negative (*pin*) photodiode
  - No internal gain, robust detector
- Avalanche Photo Diode (*APD*)
  - Advanced version with internal gain *M* due to self multiplication process
- Photodiodes are sufficiently ***reverse biased*** during normal operation → no current flow without illumination, the intrinsic region is fully depleted of carriers

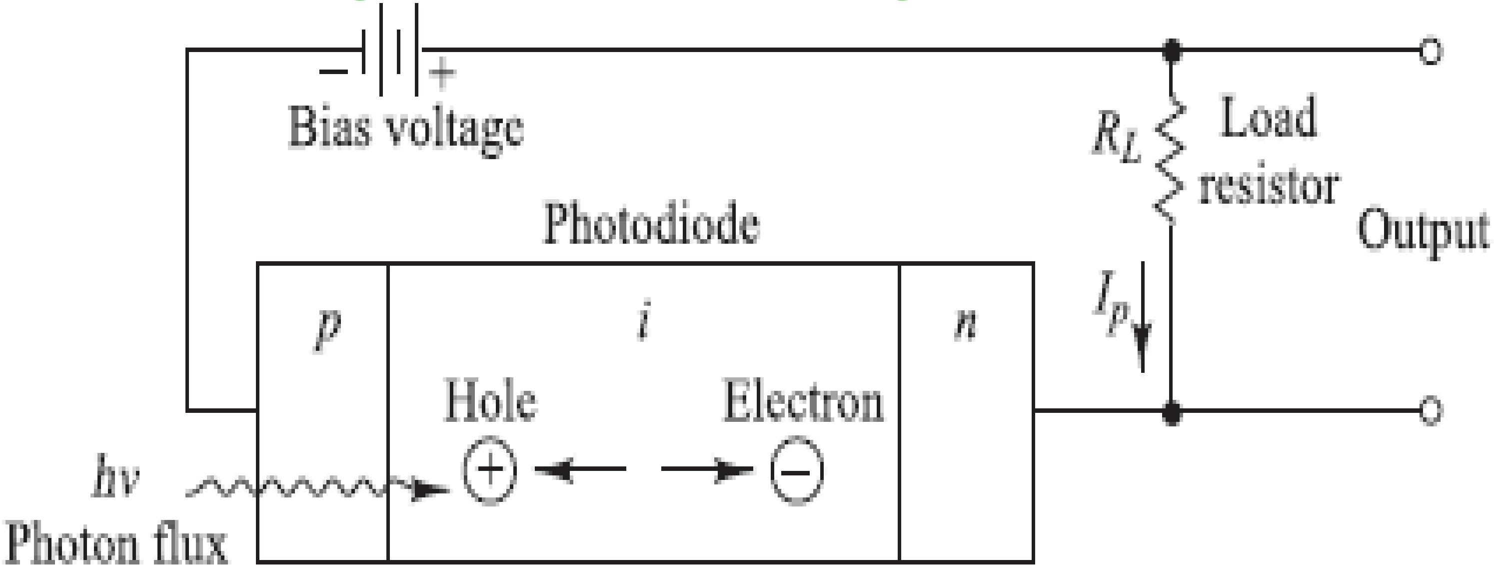
PIN DIODE

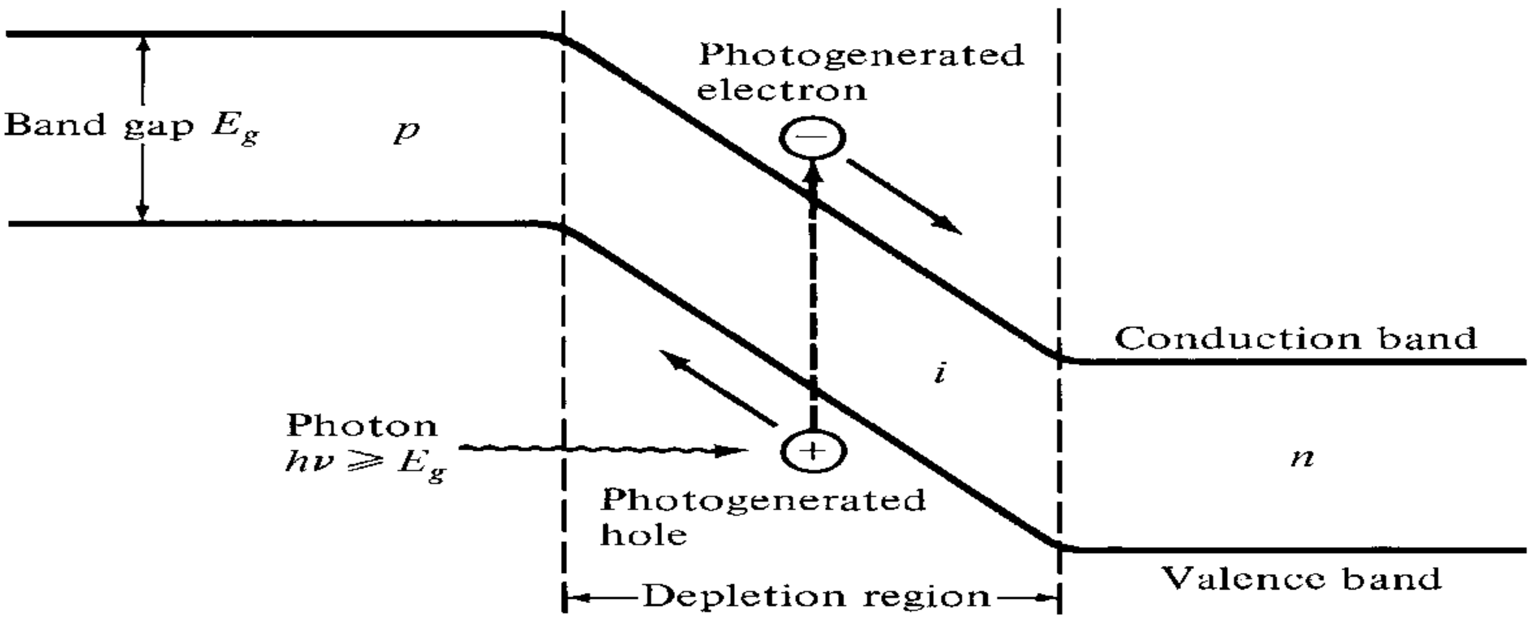
- A diode with a wide and undoped intrinsic semiconductor region between a p-type and an n-type semiconductor region.
- It was even used for microwave applications and as a photo detector as it is said to be a good light absorber.

P*i*N Photodiode

- Semiconductor positive-negative structure with an intrinsic region sandwiched between the other two regions.
- Normally operated by applying a reverse-bias voltage.
- Dark current can also be produced which is a leakage current that flows when a reverse bias is applied without incident light.

pin energy-band diagram





Structure and Working of a Pin Diode

- The PIN diode comprises a semiconductor diode having three layers naming the P-type layer, Intrinsic layer and N-type layer, as shown in the figure below.
- The P and N regions are there, and the region between them consists of the intrinsic material, and the doping level is said to be very low in this region.
-

- The thickness of the intrinsic layer is very narrow, which ranges from 10 – 200 microns.
- The P region and the N-type regions are known to be heavily doped.
- The changes in the properties of the diode are known from the intrinsic material.
- These diodes are made of silicon.
- The intrinsic region of the PIN diode acts like an inferior rectifier which is used in various devices such as attenuators, photodetectors, fast switches, high voltage power circuits, etc.

Advantage of PIN photodiodes

- The output electrical current is linearly proportional to the input optical power making it a highly linear device.
- Low bias voltage(<4v).
- Low noise
- Low dark current
- High-speed response

Quantum Efficiency

- The *quantum efficiency* η is the number of the electron–hole carrier pairs generated per incident–absorbed photon of energy $h\nu$ and is given by

$$\eta = \frac{no.of\ electron - hole\ pairs\ generated}{no.of\ incident - absorbed\ photons} = \frac{Ip/q}{Pin/h\nu}$$

I_p is the photocurrent generated by a steady-state optical power P_{in} incident on the photodetector.

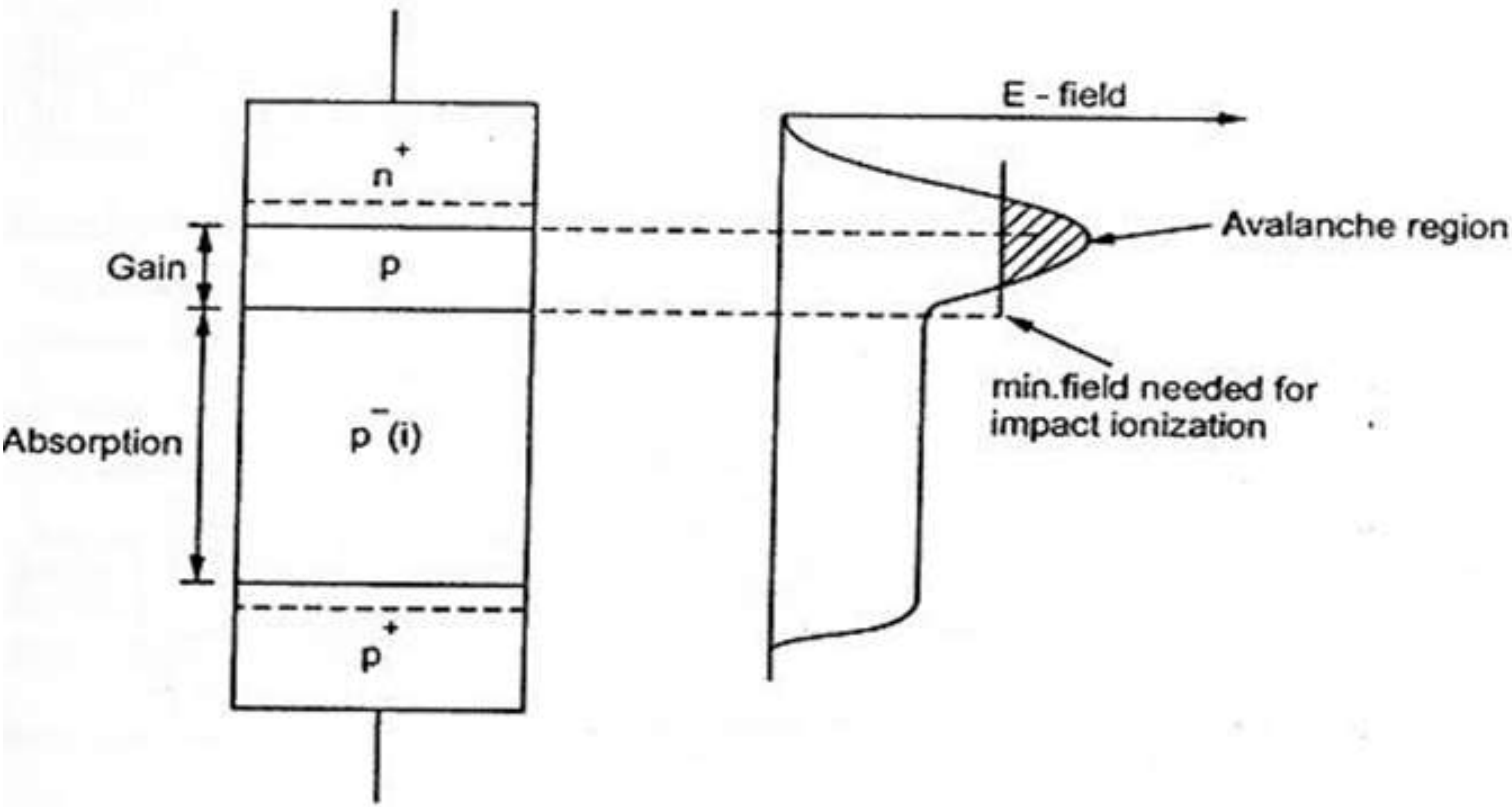
The performance of photo diode is characterized by ***responsivity R***

$$R = Ip/P_0 = nq/hv \quad (A/W)$$

Avalanche Photodiode (APD)

- APD has an internal gain M, which is obtained by having a high electric field that energizes photo-generated electrons.
- These electrons ionize bound electrons in the valence band upon colliding with them which is known as *impact ionization*
- The newly generated electrons and holes are also accelerated by the high electric field and gain energy to cause further impact ionization
- This phenomena is the *avalanche effect*

RAPD (Reach Through APD): $P^+\pi PN^+$



APD Schematic and variation of E-field across diode

Responsivity ($\Re$)

APD's have an internal gain *M*, hence

$$\Re_{APD} = \Re_{PIN} M$$

where, $M = I_M / I_p$

I_M : Mean multiplied current

M = 1 for PIN diodes

advantages

- Low level light can be detected
- Increase in sensitivity of receiver
- SNR is high
- Excellent linearity

disadvantages

- Complex structure
- High reverse bias voltage is required
- Additional noise

Photodetector Noise

- photodiode is generally required to detect very weak optical signals.
- requires that the photodetector and its amplification circuitry be optimized to maintain a given signal-to-noise ratio.

$$SNR = \frac{S}{N} = \frac{\text{signal power from photocurrent}}{\text{photodetector noise power} + \text{amplifier noise power}}$$

SNR Can NOT be improved by amplification

Notation: Detector Current

- The direct current value is denoted by, I_P (capitol main entry and capital suffix).
- The time varying (either randomly or periodically) current with a zero mean is denoted by, i_p (small main entry and small suffix).
- Therefore, the total current *Ip* is the sum of the DC component I_P and the AC component i_p .

$$I_P = I_p + i_p$$

$$I_p = \Re P_o$$

$$\langle i_p^2 \rangle = \mathrm{Lim}_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} i_p^2(t)dt$$

Quantum (Shot Noise)

Quantum noise arises due optical power fluctuation because light is made up of discrete number of photons

$$\left\langle i_Q^2 \right\rangle = 2qI_p BM^2 F(M)$$

$F(M)$: APD Noise Figure $F(M) \approx M^x$ $(0 \leq x \leq 1)$

I_p: Mean Detected Current

B = Bandwidth

q: Charge of an electron

Dark/Leakage Current Noise

There will be some (dark and leakage) current without any incident light. This current generates two types of noise

Bulk Dark Current Noise $\langle i_{DB}^2 \rangle = 2qI_D BM^2 F(M)$

I_D: Dark Current

Surface Leakage Current Noise $\langle i_{DS}^2 \rangle = 2qI_L B$

(not multiplied by M) I_L: Leakage Current

Thermal Noise

The photodetector load resistor R_L contributes to thermal (Johnson) noise current

$$\left\langle i_T^2 \right\rangle = 4K_B TB / R_L$$

K_B: Boltzmann's constant = 1.38054 X $10^{(-23)}$ J/K
T is the absolute Temperature

- Quantum and Thermal are the significant noise mechanisms in all optical receivers
- RIN (Relative Intensity Noise) will also appear in *analog links*

SNR

Detected current = AC (i_p) + DC (I_p)

Signal Power = $<i_p^2>M^2$

$$SNR = \frac{\langle i_p^2 \rangle M^2}{2q(I_p + I_D)M^2F(M)B + 2qI_LB + 4k_BTB/R_L}$$

Typically not all the noise terms will have equal weight.

Often thermal and quantum noise are the most significant.

$$\frac{S}{N} = \frac{\langle i_p^2 \rangle M^2}{2qI_pM^2F(M)B_e + 4k_BTB_e/R_L}$$

Noise Calculation Example

Example 6.8 An InGaAs *pin* photodiode has the following parameters at a wavelength of 1300 nm: $I_D = 4$ nA, $\eta = 0.90$, $R_L = 1000\,\Omega$, and the surface leakage current is negligible. The incident optical power is 300 nW (–35 dBm), and the receiver bandwidth is 20 MHz. Find the various noise terms of the receiver.

Solution: (*a*) First, we need to find the primary photocurrent. From Eq. (6.6),

$$I_p = \mathscr{R}P_{in} = \frac{\eta q}{h\nu}P_{in} = \frac{\eta q\lambda}{hc}P_{in}$$

$$= \frac{(0.90)(1.6\times10^{-19}\ \text{C})(1.3\times10^{-6}\ \text{m})}{(6.625\times10^{-34}\ \text{J}\cdot\text{s})(3\times10^{8}\ \text{m/s})}3\times10^{-7}\ \text{W}$$

$$= 0.282\ \mu\text{A}$$

(*b*) From Eq. (6.13), the mean-square shot noise current for a *pin* photodiode is

$$\langle i_{\text{shot}}^2\rangle = 2qI_pB_e$$

$$= 2(1.6\times10^{-19}\ \text{C})(0.282\times10^{-6}\ \text{A})(20\times10^{6}\ \text{Hz})$$

$$= 1.80\times10^{-18}\ \text{A}^2$$

or $\langle i_{\text{shot}}^2\rangle^{1/2} = 1.34\ \text{nA}$

(*c*) From Eq. (6.14), the mean-square dark current is

$$\langle i_{DB}^2\rangle = 2qI_DB_e$$

$$= 2(1.6\times19^{-19}\ \text{C})(4\times10^{-9}\ \text{A})(20\times10^{6}\ \text{Hz})$$

$$= 2.56\times10^{-20}\ \text{A}^2$$

or

$$\langle i_{DB}^2\rangle^{1/2} = 0.16\ \text{nA}$$

(*d*) The mean-square thermal noise current for the receiver is found from Eq. (6.17) as

$$\langle i_T^2\rangle = \frac{4k_BT}{R_L}B_e = \frac{4(1.38\times10^{-23}\ \text{J/K})(293\text{K})}{1\ \text{k}\Omega}B_e$$

$$= 323\times10^{-18}\ \text{A}^2$$

or

$$\langle i_T^2\rangle^{1/2} = 18\ \text{nA}$$

Thus for this receiver the rms thermal noise current is about 14 times greater than the rms shot noise current and about 100 times greater than the rms dark current.

Limiting Cases for SNR

- When the optical signal power is relatively high, then the shot noise power is much greater than the thermal noise power. In this case the SNR is called *shot-noise* or *quantum noise limited*.
- When the optical signal power is low, then thermal noise usually dominates over the shot noise. In this case the SNR is referred to as being *thermal-noise limited*.

Example 6.9 Consider the InGaAs *pin* photodiode described in Example 6.8. What is the SNR in decibels?

Solution: Since the dark current noise is negligible compared to the shot noise and thermal noise, we can substitute the numerical results into Eq. (6.18*b*) to get

$$\frac{S}{N} = \frac{(0.282 \times 10^{-6})^2}{1.80 \times 10^{-18} + 323 \times 10^{-18}} = 245$$

In decibels the SNR is

$$\frac{S}{N} = 10 \log 245 = 23.9$$

Limiting Cases of SNR

In the shot current limited case the SNR is:

$$SNR = \frac{\langle i_p^2 \rangle}{2q(I_p)F(M)B}$$

For analog links, there will be *RIN (Relative Intensity Noise)* as well

$$SNR = \frac{\langle i_p^2 \rangle M^2}{\left[2q(I_p + I_D)M^2 F(M) + 4k_B T / R_L + (RIN) I_p^2\right]B}$$

Detector Response Time

It is defined as time required by generated photo carriers to travel across the depletion region.

It depends mainly on

1.Transit time

2.Diffusion time

3.RC time constant

$$t_d = w/v_d$$

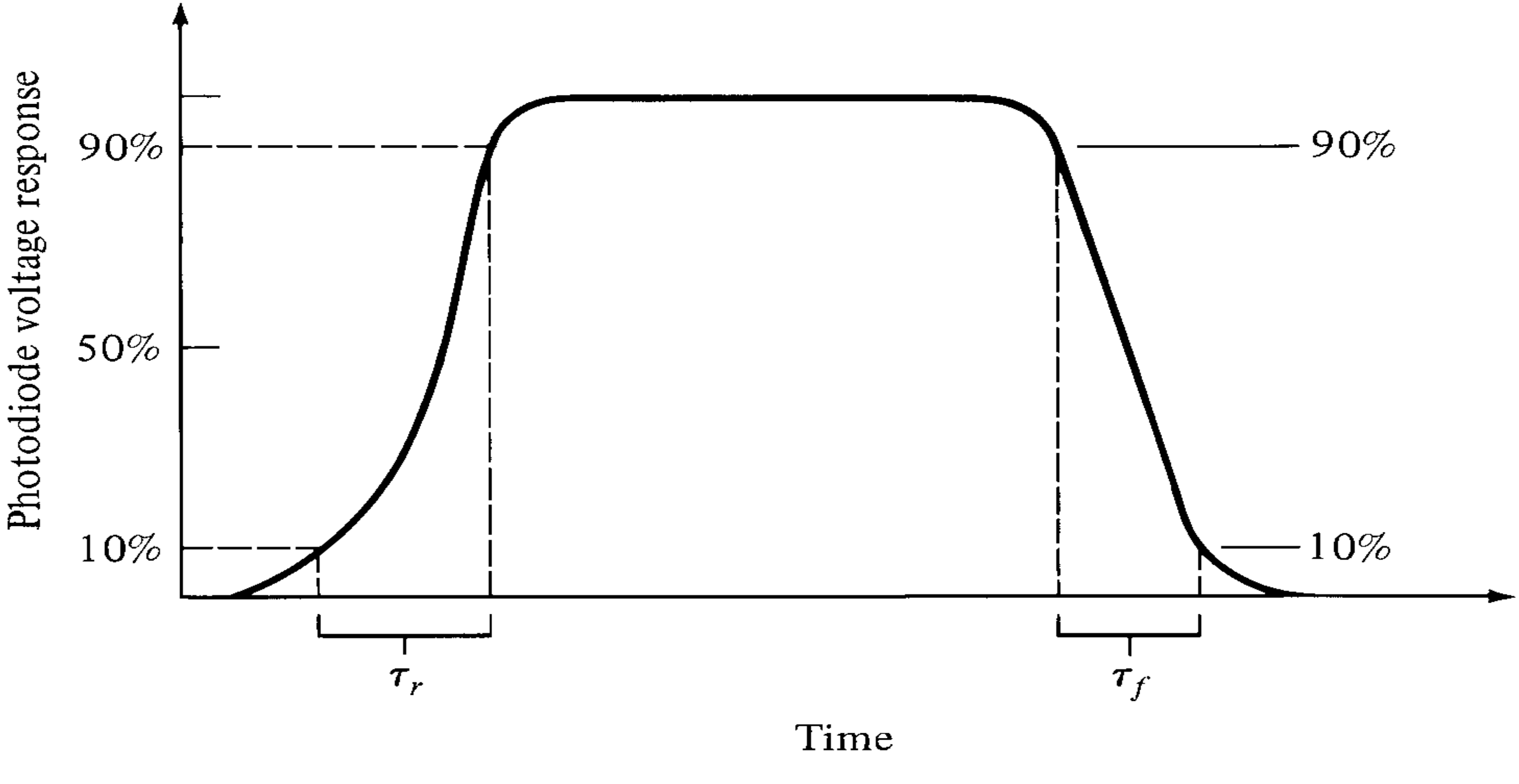
For a high speed Si PD, t_d = 0.1 ns

Transit time

- It depends on carrier drift velocity and depletion layer.it is given by

$$t_d = w / v_d$$

Diffusion time



6.15 AVALANCHE MULTIPLICATION NOISE

In APD, the noise generated due to avalanche process is known as Avalanche multiplication noise. Secondary carriers are generated due to impact ionization. Rate of generation of these carriers is statistical in nature, which causes the variations in number of photogenerated carriers. This results in noise current generation.

Mean square gain is greater than square of the average gain i.e.

$$\langle m^2 \rangle > \langle m \rangle^2 = M^2 \quad \ldots (6.67)$$

where, M = Statistically varying gain

$\langle m \rangle = M$ = Average carrier gain

Noise in APD is relatively high because noise generated by avalanche process depends on mean square gain i.e.

$$\langle m^2 \rangle = M^{x+2} \quad \ldots (6.68)$$

where, x varies between 0 and 1 depending on material and structure.

Excess noise factor F(M) is defined as the ratio of actual noise generated in APD to the noise that would exist if all the carrier pairs were multiplied by exactly M.

$$F(M) = \frac{\langle m^2 \rangle}{M^2} \quad \ldots (6.69)$$

Excess noise factor is a measure of increase in detector noise resulting from statistical multiplication process.

From Eq.(6.68) and (6.69), we get,

$$F(M) = \frac{M^{x+2}}{M^2}$$

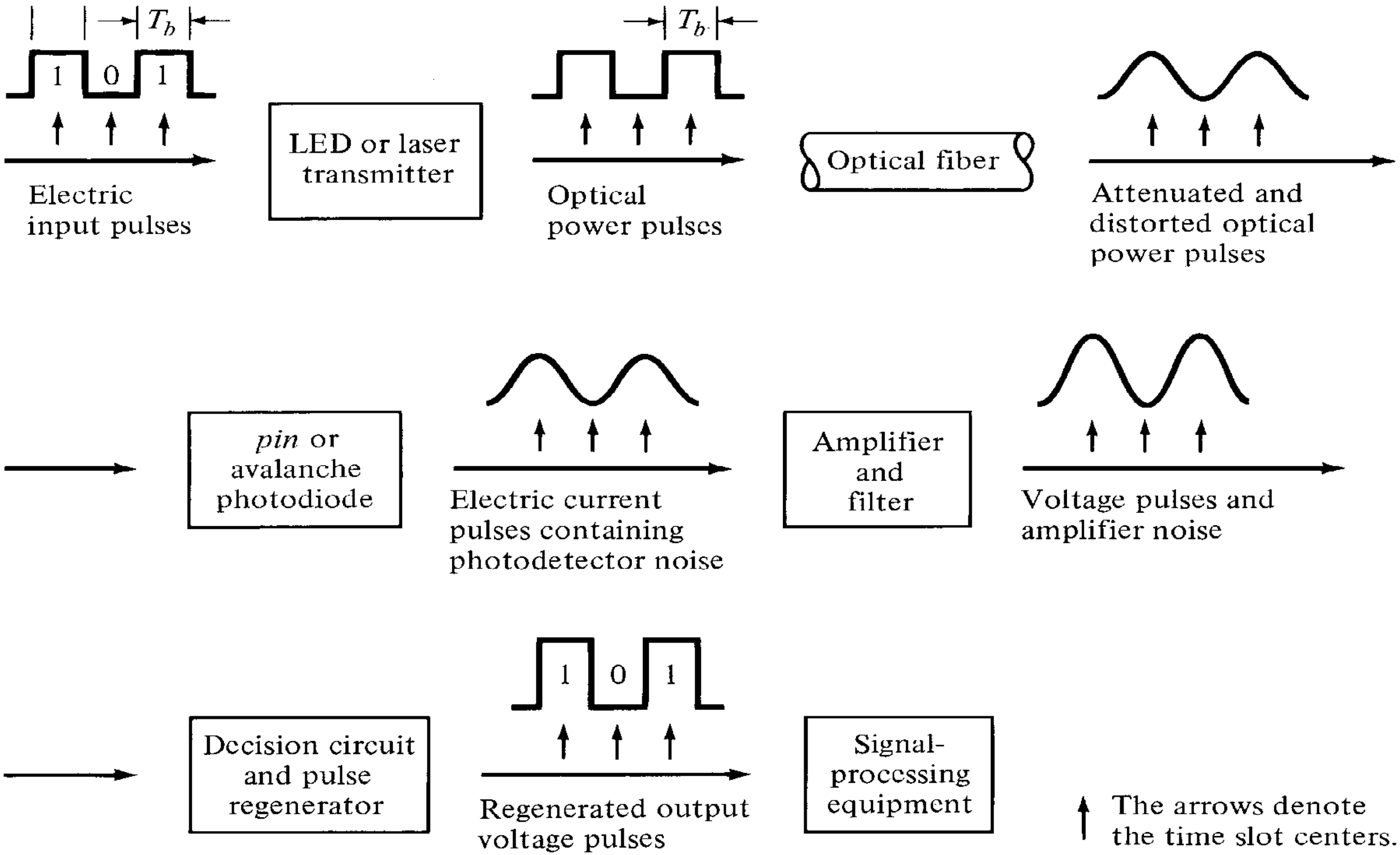
$$\therefore F(M) = M^x \quad \ldots (6.70)$$

6.16 STRUCTURE OF InGaAs APD

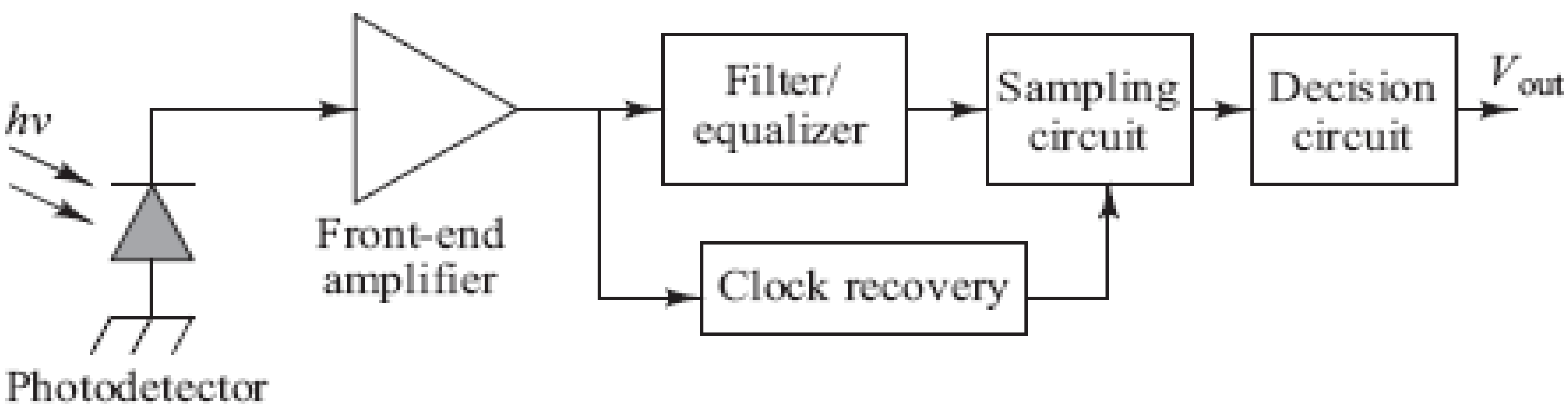
COMPARISON OF DIFFERENT PHOTODETECTORS

Sr. No.	Parameters	PIN photodiode	APD
1)	Sensitivity	Less sensitive	More sensitive
2)	Reverse bias voltage	Low	High
3)	Wavelength range	300 - 1100 nm	400 - 1000 nm
4)	Gain	No internal gain	Internal gain
5)	SNR	Poor	Better
6)	Detector circuit	Simple	Complex
7)	Cost	Low	Expensive
8)	Responsivity	0.5 to 1.0 A/W	0.5 to 100 A/W

Fundamental Receiver operation



Fundamental Receiver Operation

- The first receiver element is a *pin* or an avalanche photodiode, which produces an electric current proportional to the received power level.
- Since this electric current typically is very weak, a *front-end amplifier* boosts it to a level that can be used by the following electronics.
- After being amplified, the signal passes through a *low-pass filter* to reduce the noise that is outside
- 

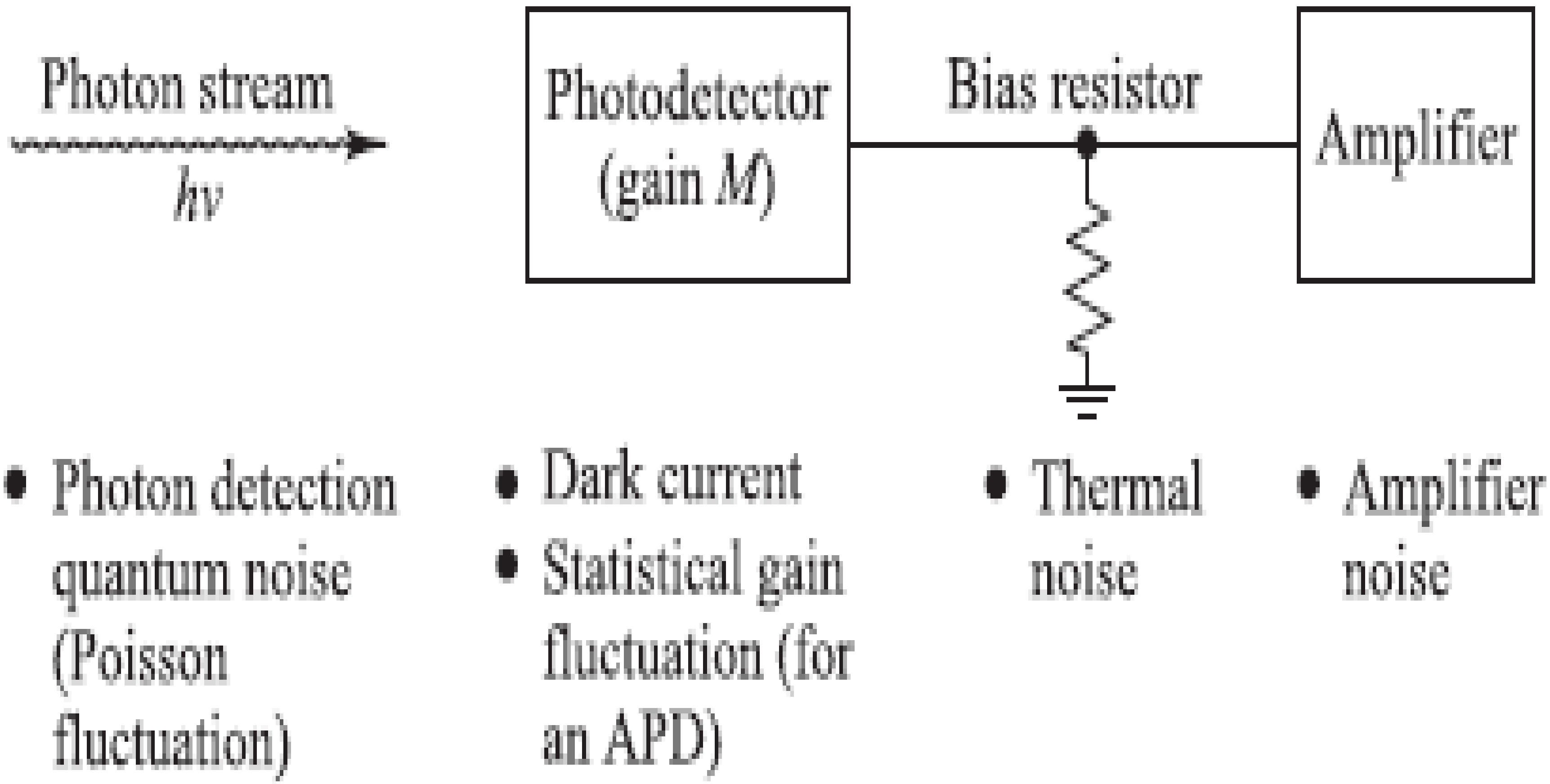
Preamplifiers

- Optical amplifier being used as a front-end preamplifier for an optical receiver.
- A weak optical signal is amplified before photo-detection so that signal to noise ratio degradation due to noise can be suppressed in the receiver.
- It provides a larger gain factor and BW.
- Three types: semiconductor optical amplifiers, Raman Amplifiers and Erbium doped fibre amplifiers.

Error Sources

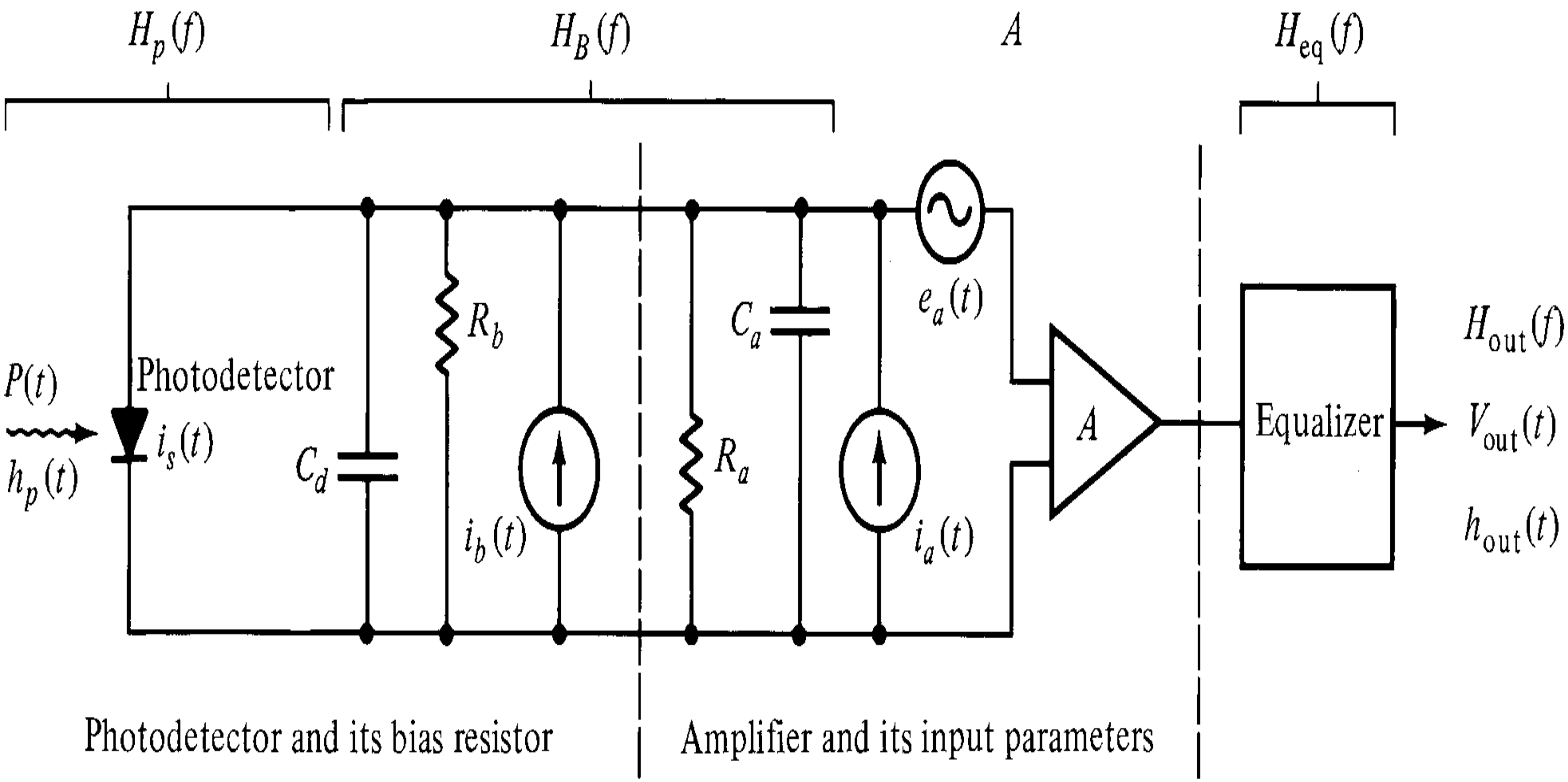
The term *noise* describes unwanted components of an electric signal that tend to disturb the transmission and processing of the signal

- The random arrival rate of signal photons produces quantum (shot) noise
- Dark current comes from thermally generated e-h pairs in the *pn* junction
- Additional shot noise arises from the statistical nature of the APD process
- Thermal noises arise from the random motion of electrons in the detector load resistor and in the amplifier electronics



Photon stream
hv
Photodetector (gain M)
Bias resistor
Amplifier
• Photon detection quantum noise (Poisson fluctuation)
• Dark current
• Statistical gain fluctuation (for an APD)
• Thermal noise
• Amplifier noise

Receiver configuration



$$B = 1/2\pi R_T C_T$$

Bandwidth of the front end:

C_T: Total Capacitance = $C_d + C_a$

R_T: Total Resistance = $R_b \,//\, R_a$

Receiver Sensitivity

- A specific minimum average optical power level must arrive at the photodetector to achieve a desired BER at a given data rate. The value of this minimum power level is called the *receiver sensitivity.*
- Assuming there is no optical power in a received zero pulse, then the receiver sensitivity is

$$P_{\text{sensitivity}} = (1/\mathscr{R})\frac{Q}{M}\left[\frac{qMF(M)BQ}{2} + \sigma_T\right]$$

$$\sigma_T^2 = \frac{4k_BT}{R_L}F_n\frac{B}{2}$$

Receiver Sensitivity Calculation

The receiver sensitivity as a function of bit rate will change for a given photodiode depending on values of parameters such as wavelength, APD gain, and noise figure.

Example 7.5 To see the behavior of the receiver sensitivity as a function of the BER, first consider the receiver to have a load resistor $R_L = 200\ \Omega$ and let the temperature be $T = 300°K$. Letting the amplifier noise figure be $F_n = 3$ dB (a factor of 2), then from Eq. (7.20) the thermal noise current variance is $\sigma_T = 9.10 \times 10^{-12} B^{1/2}$. Next, select an InGaAs photodiode with a unity-gain responsivity $\mathcal{R} = 0.95$ A/W at 1550 nm and assume an operating BER $= 10^{-12}$ so that a value of $Q = 7$ is needed. If the photodiode gain is M, then the receiver sensitivity is

$$P_{\text{sensitivity}} = \frac{7.37}{M}\left[5.6 \times 10^{-19} MF(M)B + 9.10 \times 10^{-12} B^{1/2}\right] \qquad (7.22)$$

Example 7.7 Consider an InGaAs avalanche photodiode for which $M = 10$ and $F(M) = 5$. For the conditions in Eq. (7.22), what is the receiver sensitivity at a 1-Gb/s data rate for a 10^{-12} BER requirement?

Solution: From Eq. (7.22) we have

$$P_{sensitivity} = 0.737\left[5.6 \times 10^{-19}(50)(1 \times 10^{9}) + 9.10 \times 10^{-12}(1 \times 10^{9})^{\frac{1}{2}}\right]$$

$$= 2.32 \times 10^{-4} \text{ mW} = -36.3 \text{ dBm}$$

The Quantum Limit

- The *minimum received optical power* required for a specific bit-error rate performance in a digital system.
- This power level is called the *quantum limit*, since all system parameters are assumed ideal and the performance is limited only by the detection statistics.

Example 7.8 A digital fiber optic link operating at 850 nm requires a maximum BER of 10^{-9}.

(*a*) Let us first find the quantum limit in terms of the quantum efficiency of the detector and the energy of the incident photon. From Eq. (7.23) the probability of error is

$$P_r(0) = e^{-\bar{N}} = 10^{-9}$$

Solving for $\bar{N}$, we have $\bar{N} = 9 \ln 10 = 20.7 \sim 21$. Hence, an average of 21 photons per pulse is required for this BER. Using Eq. (7.1) and solving for E, we get

$$E = 20.7 \frac{h\nu}{\eta}$$

(*b*) Now let us find the minimum incident optical power P_i that must fall on the photodetector to achieve a 10^{-9} BER at a data rate of 10 Mb/s for a simple binary-level signaling scheme. If the detector quantum efficiency $\eta = 1$, then

$$E = P_i\tau = 20.7h\nu = 20.7\frac{hc}{\lambda}$$

where $1/\tau$ is one-half the data rate B; that is, $1/\tau = B/2$. (*Note:* This assumes an equal number of 0 and 1 pulses.) Solving for P_i,

$$P_i = 20.7\frac{hcB}{2\lambda}$$

$$= \frac{20.7(6.626 \times 10^{-34}\ \text{J·s})(3.0 \times 10^{8}\ \text{m/s})(10 \times 10^{6}\ \text{bits/s})}{2(0.85 \times 10^{-6}\ \text{m})}$$

$$= 24.2\ \text{pW}$$

or, when the reference power level is 1 mW,

$$P_i = -76.2\ \text{dBm}$$

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Department of Electronics and Communication Engineering

OPTICAL FIBER COMMUNICATION

Unit-IV

OPTICAL FIBER SYSTEM DESIGN AND TECHNOLOGY

Contents

- System specification
- Point-to- links
- link power budget
- Rise Time Budget
- Bandwidth Budget
- Power Budget and Receiver Sensitivity
- Link Budget calculations
- Optical Multiplexing & Demultiplexing techniques
- Optical Amplifiers and its Applications.

System Specifications:

Photodetector, Optical Source, Fiber

- Photodetectors: Compared to APD, PINs are less expensive and more stable with temperature. However PINs have lower sensitivity.
- Optical Sources:

1- **LED**s: 150 (Mb/s).km @ 800-900 nm and larger than 1.5 (Gb/s).km @ 1330 nm

2- InGaAsP **lasers**: 25 (Gb/s).km @ 1330 nm and ideally around 500 (Gb/s).km @ 1550 nm. 10-15 dB more power. However more costly and more complex circuitry.

- Fiber:

1- Single-mode fibers are often used with lasers or edge-emitting LEDs.

2- Multi-mode fibers are normally used with LEDs. NA and Δ should be optimized for any particular application.

Point-to-Point Link

- The components must be carefully chosen to ensure the desired performance level and can be maintained for the expected system life time.

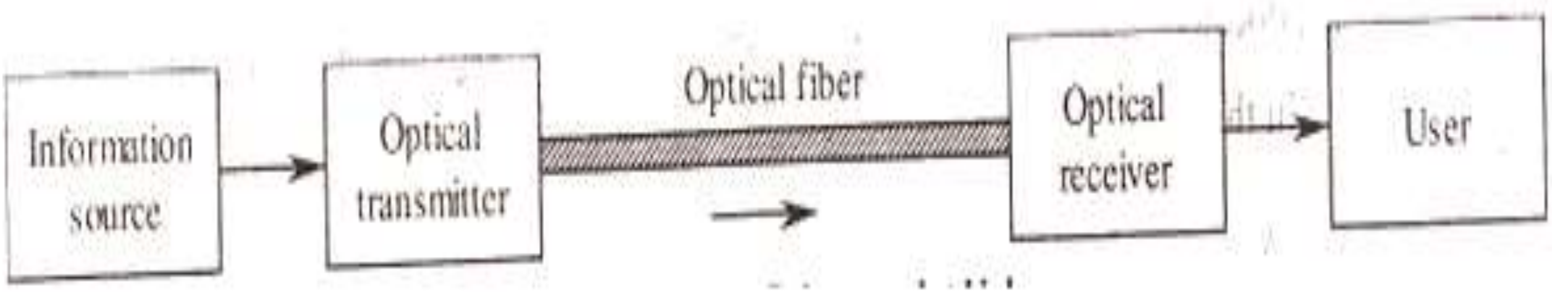


Fig 7.2.1 Simplex Point-to-Point Link

Figure represents the block diagram of a simplex point-to-point link. The three major optical links building blocks are,

Transmitter, Receiver and Optical fiber.

The key system requirements are needed in analyzing a link.

- Signal dispersion
- Data rate
- Transmission distance and cost.

Optical sources (such as LED or LASER) are used based on the following characteristics.

- Emission wavelength
- Spectral line width
- Output power
- Effective radiating area
- Emission pattern
- Number of emitting modes

.

The characteristics of photo detector such as,

- Responsivity
- Operating wavelength
- Speed and
- Sensitivity

The choice of optical fiber

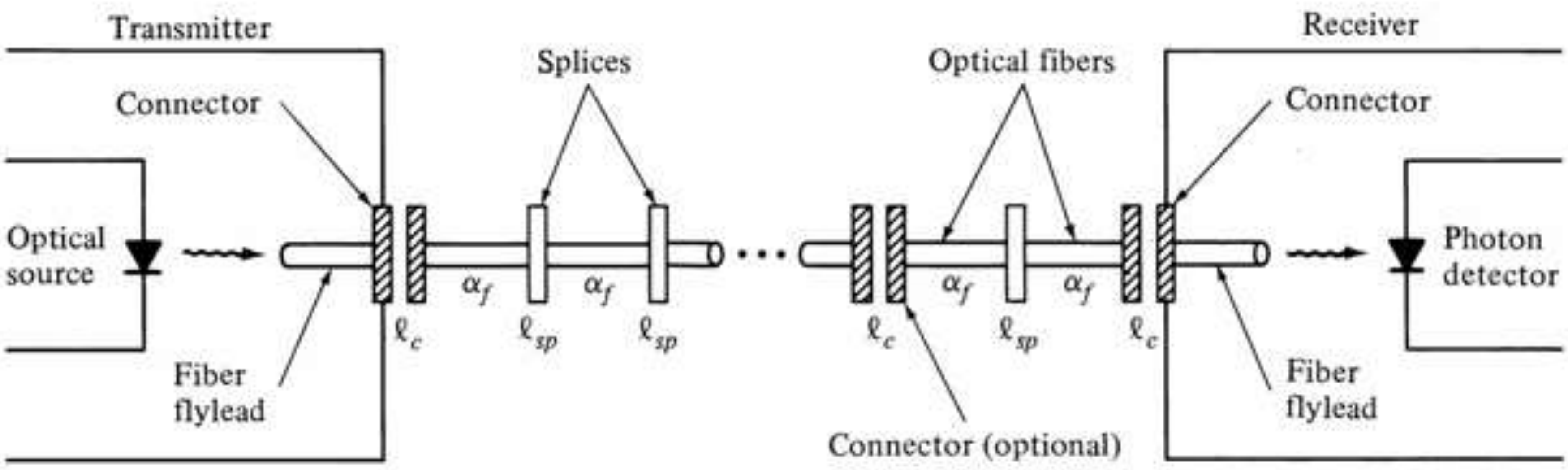
- Single mode and multimode (step or graded index)
- Core size
- Core refractive index profile
- Band width or dispersion
- Attenuation
- Numerical aperture or modefield diameter

Link Budget Considerations

(1) **Power Budget**: determines the power margin between the optical transmitter output and the minimum receiver sensitivity needed to establish a specific Bit Error Rate (BER).

(2) Bandwidth Budget: Determines dispersion limitation of optical fiber link

Link Power/Loss Analysis



Rise-Time Budget

$$t_{sys} = [t_{tx}{}^2 + t_{\mathrm{mod}}{}^2 + t_{GVD}{}^2 + t_{rx}{}^2]^{1/2}$$

$$= \left[t_{tx}{}^2 + \left(\frac{440 L^q}{B_0} \right)^2 + D^2 \sigma_\lambda{}^2 L^2 + \left(\frac{350}{B_{rx}} \right)^2 \right]^{1/2}$$

$t_{tx}[ns]$: transmitter rise time $t_{rx}[ns]$: receiver rise time $t_{\mathrm{mod}}[n]$: modal dispersion

$B_{rx}[MHz]$: 3dB Electrical BW $L[km]$: Length of the fiber $B_0[MHz]$: BW of the 1 km of the fiber;

$q \approx 0.7$ t_{GVD}[ns]: rise-time due to group velocity dispersion

$D[ns/(km.nm)]$: Dispersion σ_λ [nm]: Spectral width of the source

Total Rise time, T_{sys}:

$$T_{sys}=1.1(T_{TX}^2+T_{RX}^2+T_{fiber}^2)^{1/2}$$

What is a good Rise time?

- For a good reception of signal
  $T_{sys} \leq 0.7$ x Pulse Width (PW)

- PW = 1/BitRate for NRZ
  1/2BitRate for RZ

Example:
Rise Time Budget Measurement for Long Haul Application

Tx rise time, T_{TX} = 0.1 ns

Rx rise time, T_{RX} = 0.5 ns

Linewidth($\Delta\lambda$) = 0.15 nm

Dispersion Coefficient, D = 18 ps/nm-km

Fiber length = 150km

Bit Rate = 622Mbps

Format = RZ

Simple Calculation....

Fiber rise time, T_F =Length x D x Linewidth($\Delta\lambda$)

= 150 km x 18 x 0.15 nm

= 0.4 ns

Total Rise time, $T_{SYS} = 1.1\sqrt{T_{LS}^2 + T_{PD}^2 + T_F^2}$

$= 1.1\sqrt{0.01 + 0.25 + 0.16}$

$T_{SYS} = 0.77$ ns

Let say,

Bit Rate = STM 4 = 622 Mbps

Format = RZ

$T_{sys} \leq 0.7 \times \text{Pulse Width (PW)}$

$\text{Pulse Width (PW)} = 1/(622 \times 10^6)$

$= 1.6 \text{ ns}$

$0.77 \text{ ns} \leq 0.7 \times 1.6 \text{ ns}$

$0.77 \text{ ns} \leq 1.1 \text{ ns}$!!

Good Rise Time Budget!!

Let say,

Bit Rate = STM 16 = 2.5 Gbps

Format = RZ

$T_{sys} \leq 0.7 \times$ Pulse Width (PW)

Pulse Width (PW) = $1/(2.5\times10^9)$

= 0.4 ns

0.77 ns $\leq$ 0.7 x 0.4 ns

0.77 ns $\geq$ 0.28 ns !!

Bad Rise Time Budget!!

Power Budget

$P_{RX} \geq P_{MIN}$

P_{RX} = Received Power

P_{MIN} = Minimum Power at a certain BER

$P_{RX} = P_{TX}$ – Total Losses - P_{MARGIN}

P_{TX} = Transmitted Power

$P_{MARGIN} \approx 6$ dB

- Total optical loss = Connector loss + (Splicing loss + Fiber attenuation) + System margin (Pm)

$P_T = 2Lc + \alpha_f L + Lsp$+System margin (Pm)

Requirements Cont'd:

- Loss,L = $L_{IL} + L_{fiber} + L_{conn.} + L_{non\text{-}linear}$

  L_{IL} = Insertion Loss

  L_{fiber} = Fiber Loss

  $L_{conn.}$ = Connector Loss

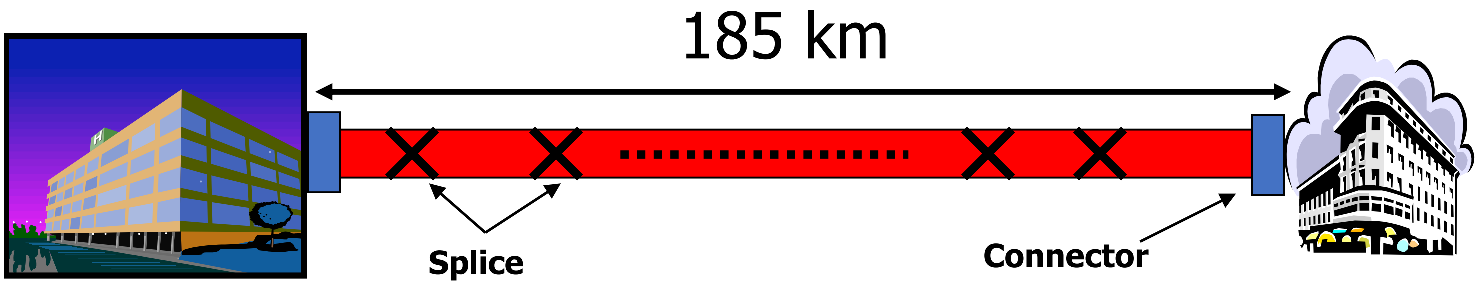
  $L_{non\text{-}linear}$ = Non-linear Loss

- Gain,G = $Gain_{amp} + G_{non\text{-}linear}$

  $Gain_{amp}$ = Amplifier Gain

  $G_{non\text{-}linear}$ = Non-linear Gain

Example:
Power Budget Measurement for Long Haul Transmission



P_{Tx} = 0 dBm

P_{SEN} = -28 dBm

Attenuation Coefficient, α = 0.25 dB/km

Dispersion Coefficient, D = 18 ps/nm-km

Number of Splice = 46

Splice Loss = 0.1 dB

Connector Loss = 0.2 dB

P_{Margin} = 6 dB

Simple Calculation….

Fiber Loss = 0.25 dB/km X 185 km
= 46.3 dB

Splice Loss = 0.1 dB X 46
= 4.6 dB

Connector Loss = 0.2 dB X 2
= 0.4 dB

Total Losses = 46.3 + 4.6 + 0.4
= 51.3 dB

P_{Margin} = 6 dB

P_{RX} = P_{TX} – Total Losses – P_{Margin}
= 0 – 51.3 – 6

P_{RX} = -57.3 dB

CONCLUSION: BAD SYSTEM!!

Power Budget, $P_{RX} \leq P_{SEN}$!!

First we calculate the amplifier's gain..

$$Gain \geq P_{SEN} - P_{RX}$$

$$Gain \geq -28 - (-57.3)$$

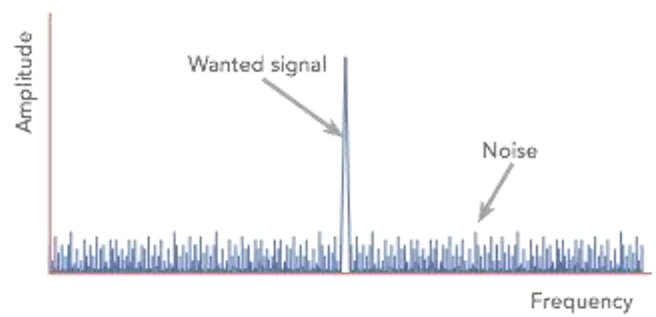
$$Gain \geq 29.3 \text{ dB}$$

To make it easy, $Gain \geq 30 \text{ dB}$

Now…Where to put the amplifier?

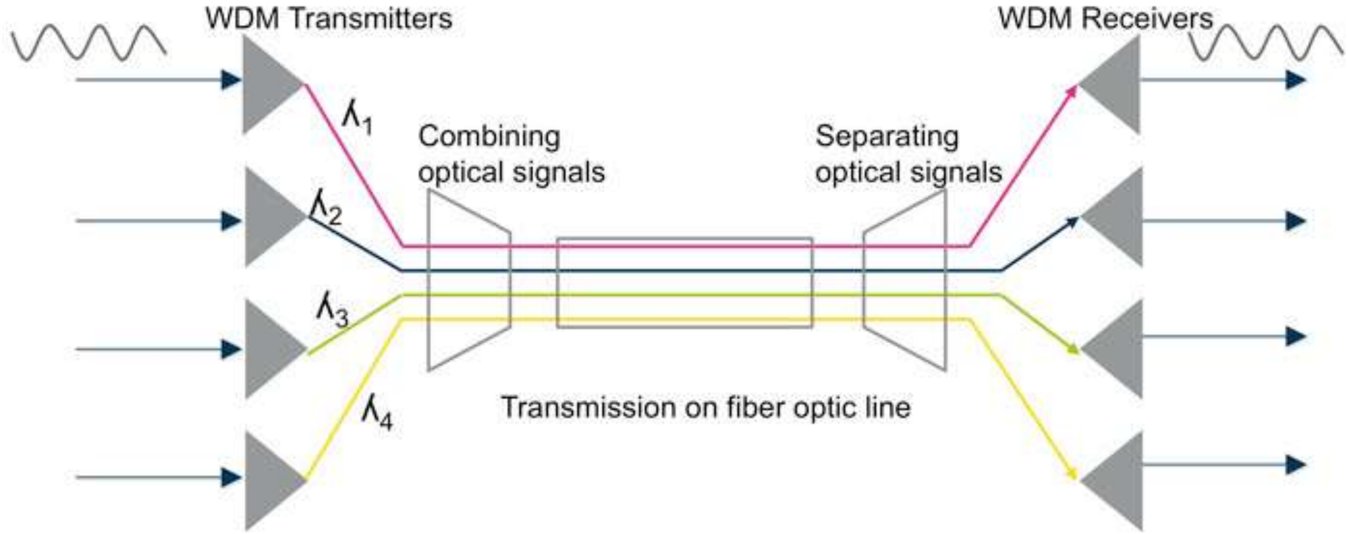
Receiver sensitivity

- ***Performance*** can be measured as a *low bit error rate* (BER).
- A measure of a ***good receiver*** is to have the *same performance* with the *lowest level of incident optical power.*
- ***BER ÷ probability of an incorrect identification of a bit by the decision circuit of a receiver.***
- ***Receiver Sensitivity*** ÷ Receiver sensitivity is **the minimum power level at which the receiving node is able to clearly receive the bits being transmitted**.


Amplitude
Wanted signal
Noise
Frequency

Optical
Multiplexing & Demultiplexing techniques

- Normally, there are three main different techniques in multiplexing light signals onto a single optical fiber link: optical time division multiplexing (OTDM), code division multiplexing (CDM), and wavelength division multiplexing (WDM).
- WDM is one of the most common way using wavelengths to increase bandwidth by multiplexing various optical carrier signals onto a single optical fiber.


WDM Transmitters
WDM Receivers
λ1
λ2
λ3
λ4
Combining optical signals
Separating optical signals
Transmission on fiber optic line

- **What Is multiplexing?**
- Multiplexing (Muxing) is a term used in the field of communications and computer networking. It generally refers to the process and technique of transmitting multiple analog or digital input signals or data streams over a single channel. Since multiplexing can integrate multiple low-speed channels into one high-speed channel for transmission, the high-speed channel is effectively utilized.
- **What Is demultiplexing?**
- Demultiplexing (Demuxing) is a term relative to multiplexing. It is the reverse of the multiplexing process. Demultiplex is a process reconverting a signal containing multiple analog or digital signal streams back into the original separate and unrelated signals.

Optical Amplifiers and its Applications

- However, when the length of the optical fiber is a distance as long as 10 km or 100 km, that transmission loss cannot be ignored. When the light (signal) propagating a long-distance optical fiber becomes extremely weak, it is necessary to amplify the light using an optical amplifier.
- An optical amplifier amplifies light as it is without converting the optical signal to an electrical signal, and is an extremely important device that supports the long-distance optical communication networks of today.

Applications of Optical Amplifiers

- **Applications of Optical Amplifiers**
- Typical applications of optical amplifiers are:
- An amplifier can boost the (average) power of a laser output to higher levels (→ ***master oscillator power amplifier*** = MOPA).
- It can generate extremely high **peak powers**, particularly in **ultrashort pulses**, if the stored energy is extracted within a short time.
- It can amplify weak signals before **photodetection**, and thus reduce the detection noise, unless the added **amplifier noise** is large.

Design of Digital systems:

System specifications:

- **Photodetectors:** Compared to APD, PINs are less expensive and more stable with temperature. However PINs have lower sensitivity.
- **Optical Sources:**

1- LEDs: 150 (Mb/s).km @ 800-900 nm and larger than 1.5 (Gb/s).km @ 1330 nm

2- InGaAsP lasers: 25 (Gb/s).km @ 1330 nm and ideally around 500 (Gb/s).km @ 1550 nm. 10-15 dB more power. However more costly and more complex circuitry.

- **Fiber:**

1- Single-mode fibers are often used with lasers or

System Rise Time

- Calculate the total rise times

  Tx, Fiber, Rx

- Calculate Fiber rise time, T_{Fiber}

  $T_{fiber} = D \times \Delta\lambda \times L$

  D = Dispersion Coefficient
  $\Delta\lambda$ = Linewidth
  L = Fiber Length

Tx Rise Time, T_{TX} = normally given by manufacturer
Rx Rise Time, T_{RX} = normally given by manufacturer

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Department of Electronics and Communication Engineering

OPTICAL FIBER COMMUNICATION

UNIT-V

Optical Networks

Optical Networks

- **Definition**: An Optical Network is basically a communication network **used for the exchange of information through an optical fiber cable** between one end to another. It is one of the quickest networks used for data communication.

CONTENTS

- **Basic Networks**
- **Broadcast-and-select WDM Networks**
- **Wavelength routed Networks**
- **Performance of WDM+EDFA Networks**
- **Ultra high capacity networks**

Basics Of Networks

Station : Stations in an optical network serves as the source and destination of the information being transmitted and received.

Examples: computers, terminals, telephones or other equipment for communicating.

Network:

The pattern of contacts or flow of information between the stations is called a network.

Node:

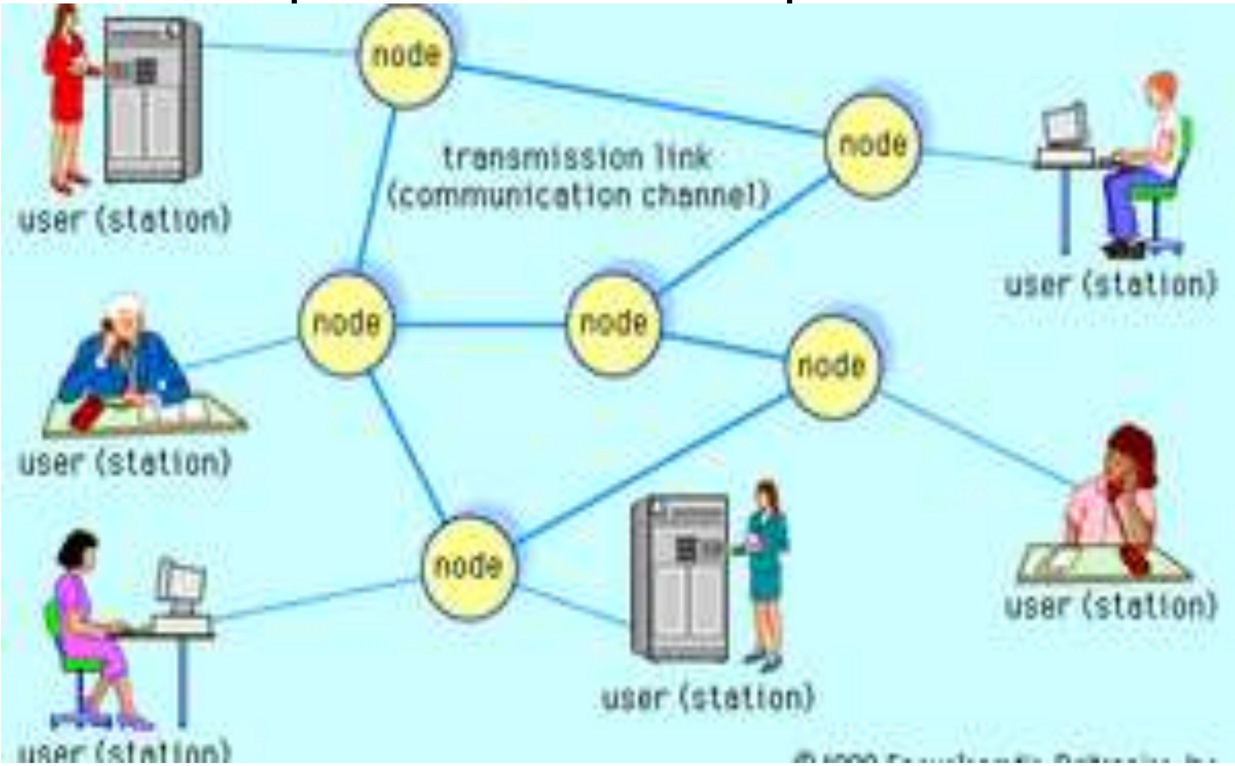
Node is nothing but acts as a hub for multiple transmission lines inside the network. In case of a single transmission line, an optical network does not require nodes, as in this case stations at both the ends can be directly connected to the fiber cables.

Trunk: A trunk is basically a transmission line i.e., optical fiber cable in order to transmit the optical signal.

Topology:

When multiple fiber cables are employed in an optical network, then these are connected through nodes. But the way in which the multiple nodes are connected together denotes the topology of the network.

Router : A router is basically placed inside an optical network that provides a suitable path for signal transmission.



Networks classification:

LANs :

LANs means Local area networks. It is a interconnect users in a localized area such as a department, a building, an office or factory complex, or a university campus .

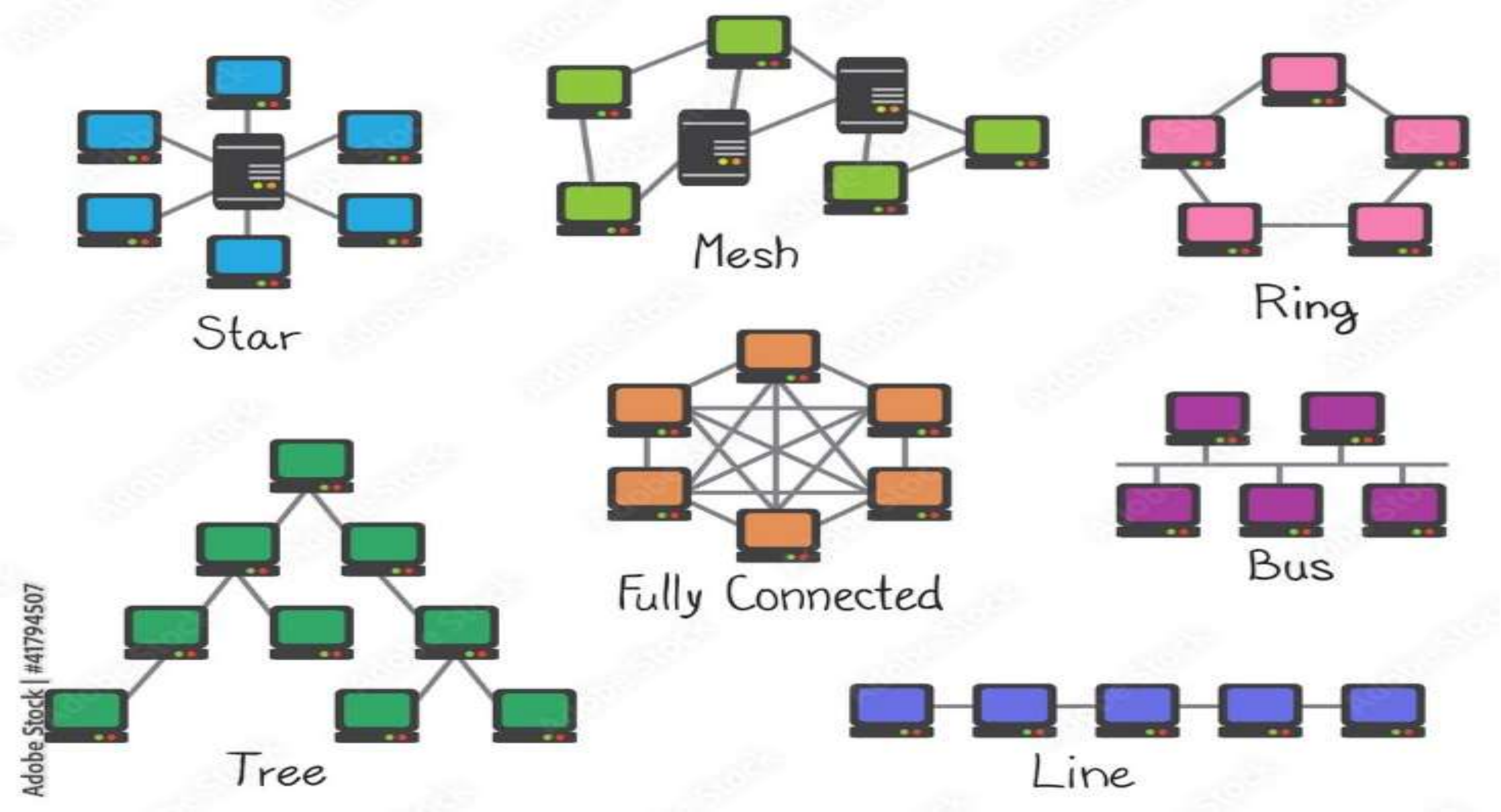
MANs :

MANs means Metropolitan area networks. which provides user connection with in a city or in the metropolitan area surrounding a city.

WANs :

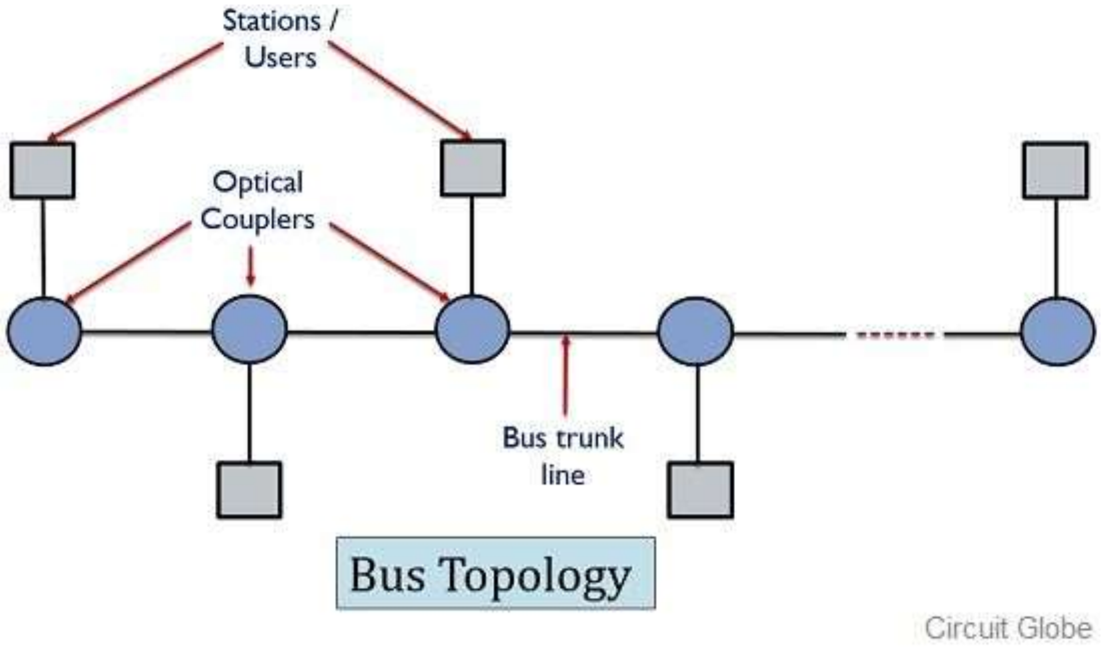
WANs means wide area network. it covers a large geographical area ranging from connection between near by cities to connection of users across a country.

Network Topologies :

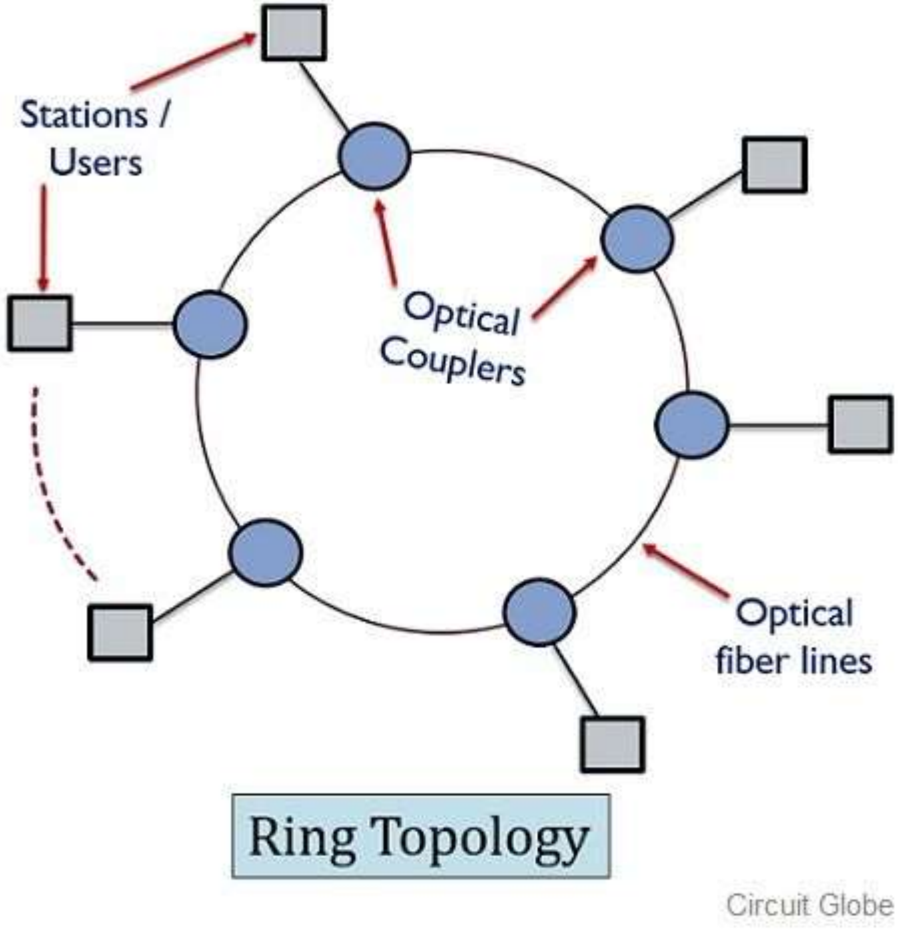


- The popular protocol used in optical LANs is the Fiber Distributed Data Interface (FDDI).
- SONET and SDH are two protocols which are widely used on a ring network with active nodes in MANs and WANs.

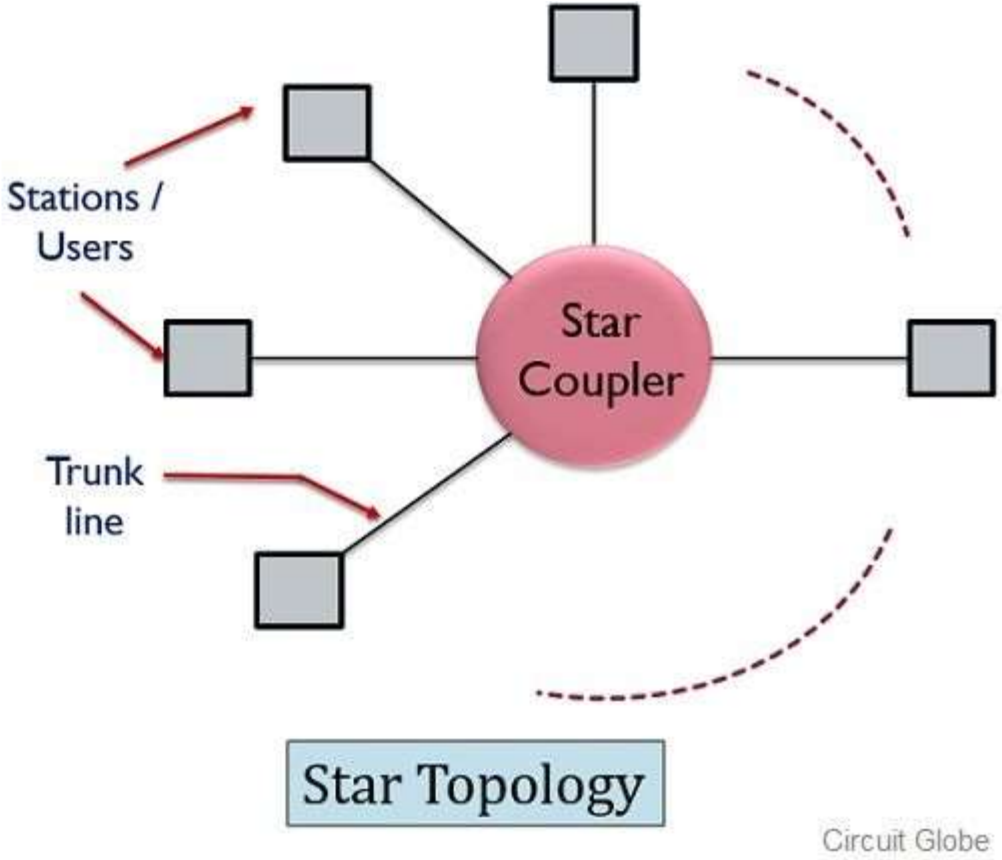
- **Bus Topology**: In a bus topology, the various nodes are connected through a single trunk line with the help of optical couplers. This allows a convenient as well as a cost-effective method to transmit the signal. However, in a bus topology, it is difficult to determine the faulted node as well as it also takes time to restore the transmitted signal from that particular node.



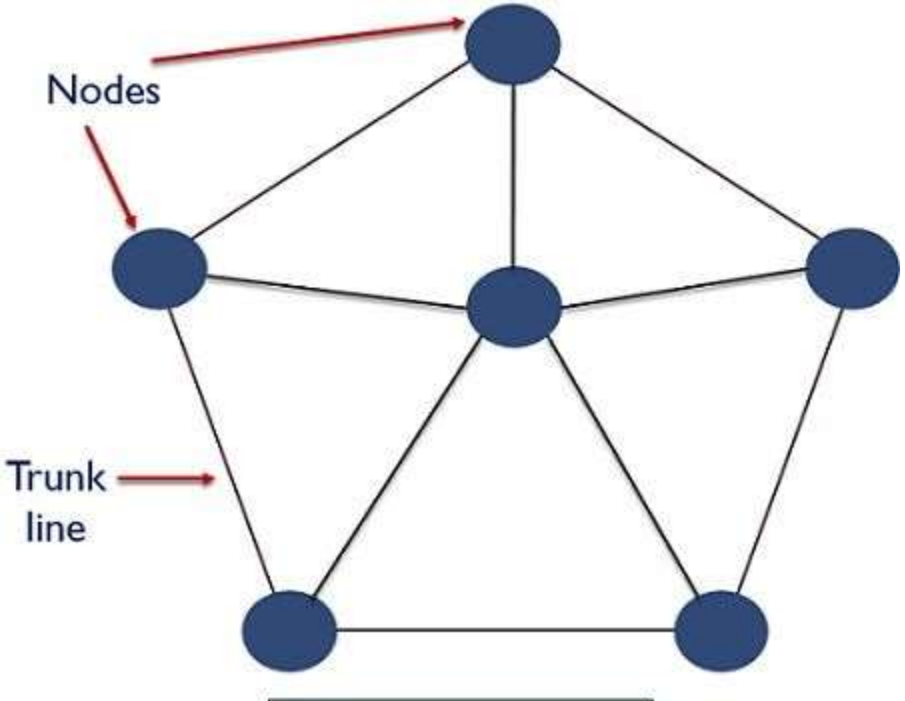
- **Ring Topology**: In a ring topology, one single node is joined to its neighbouring node thereby forming a closed path. So, the transmitted information in the form of light is sent from one node to another.



- **Star Topology**: In star connection, the various nodes of the network are connected together with a single central hub. This central hub can be active or passive network. This central hub then controls and directs the transmitted optical signal inside the optical network.

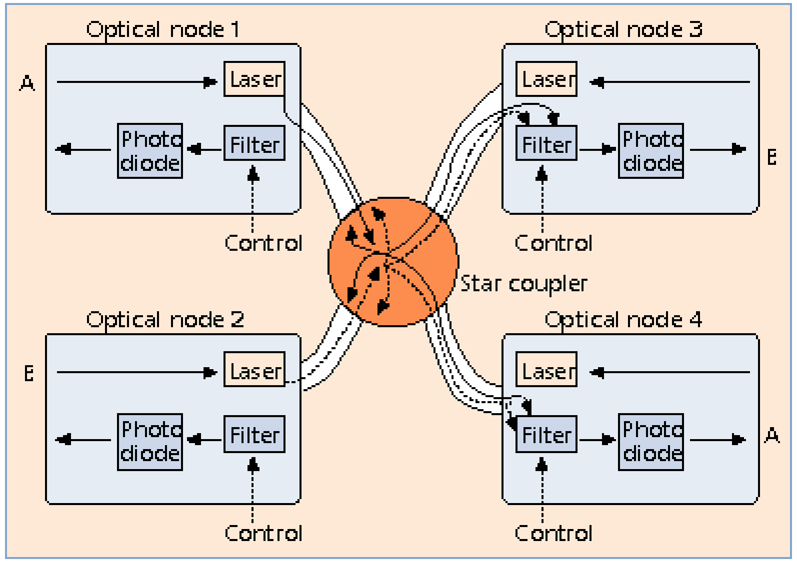


- **Mesh Topology**: In a mesh topology, an arbitrary connection is formed between the nodes in the network. This point to point connection can Basically, in mesh connection, failure of any link or node is generated then firstly that particular failure is detected and then the signal traffic is diverted from failed node to another link inside the connection. be changed according to the application.



Broadcast-and-Select Network

Broadcast-and-select networks are **based on a passive star coupler device connected to several stations in a star topology**.



Broadcast-and-Select WDM Network

All-optical WDM networks have full potential of optical transmission capacity and versatility of communication networks beyond SONET architectures.

- These networks can be classified as

(1) Broadcast-and-select techniques

(2) Wavelength-routing networks.

- Broadcast-and select techniques employing passive optical stars, buses and wavelength routers are used for local networks can be classified as

(1) Single-hop networks

(2) Multi-hop networks

- Single hop refers to network where information transmitted in the form of light reaches its destination without being converted to an electrical form at any intermediate point. In a multi hop network, intermediate electro-optical conversion can occurred.

Broadcast and Select Signal Hop Network

- Two alternate physical architectures for a WDM-based local network have n sets of transmitters and receivers are attached to either a star coupler or a passive bus.

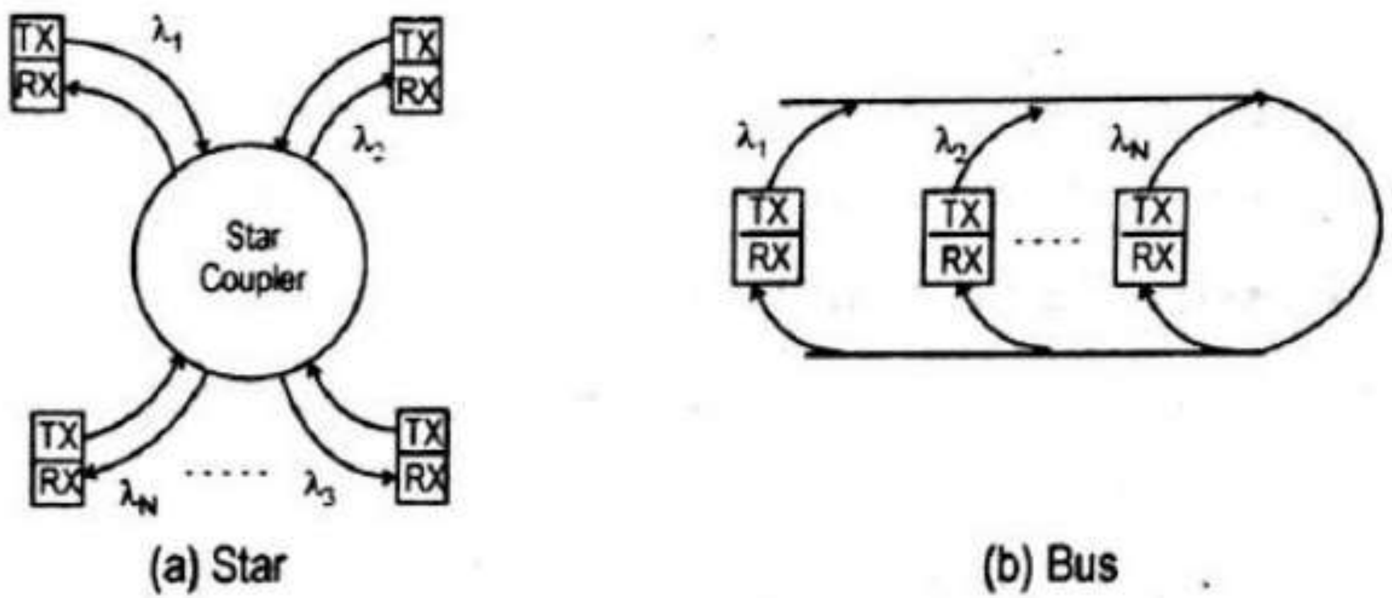


Figure 5.5 Physical architecture of WDM based local network

Each transmitter sends its information at a fixed wavelength.

- All the transmissions from the various nodes are combined in a pasive star. Coupler or coupled onto a bus and sent out to all receivers.
- An interesting point to note is that the WDM setup is protocol transparent.

Protocol transparent means that different sets of communicating nodes can use different information exchange rules (protocols) without affecting the other nodes in the network.

- The architectures of single-hop broadcast-and-select networks are fairly simple, there needs to be careful dynamic coordination between the nodes.
- A transmitter sends its selective filter to that wavelength.
- Two sending stations need to coordinate their transmission so the collisions of information streams at the some wavelength do not occur.

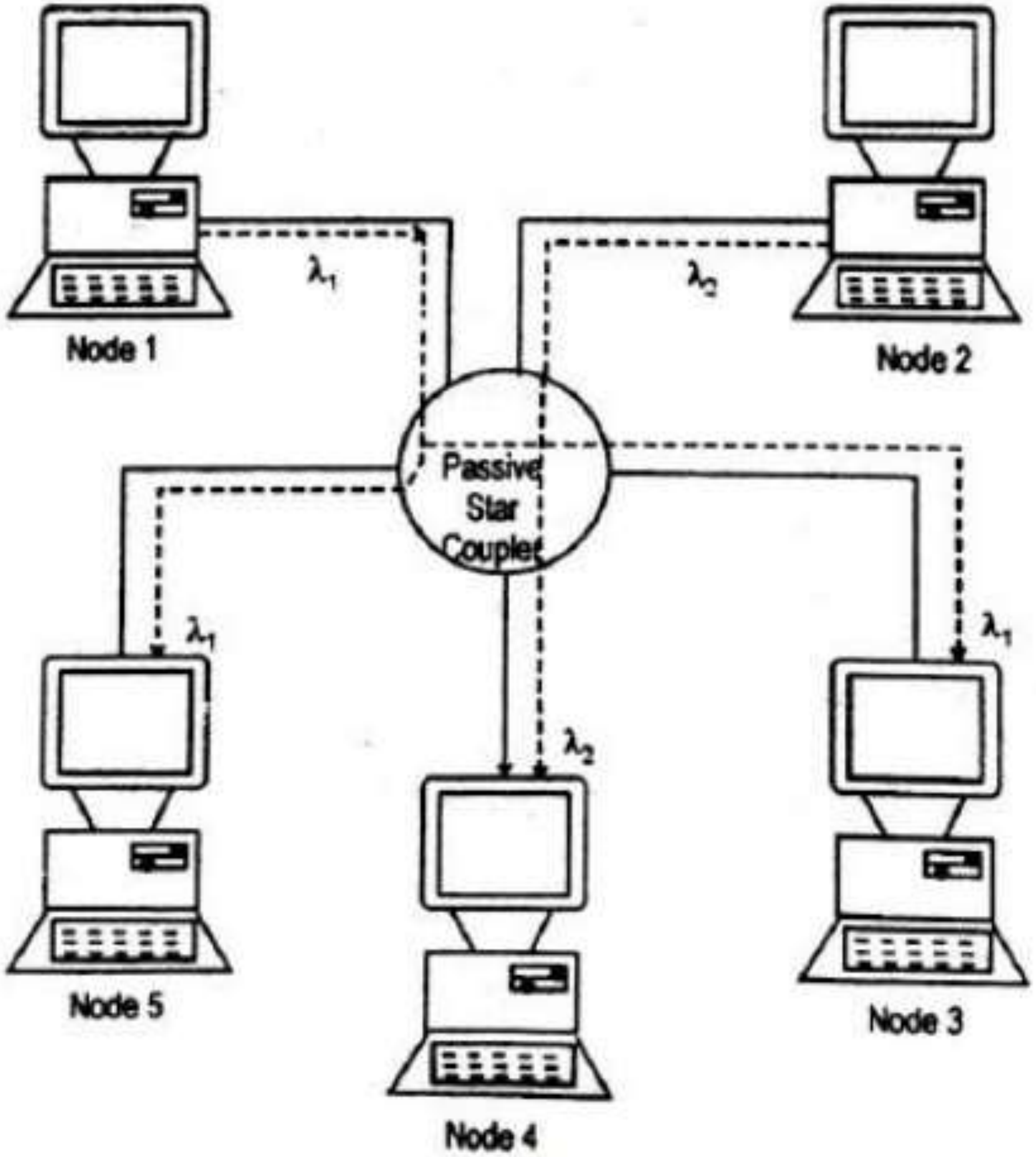


Figure 5.6 Architecture of single hop network

Broadcast and Select Multi hop Network

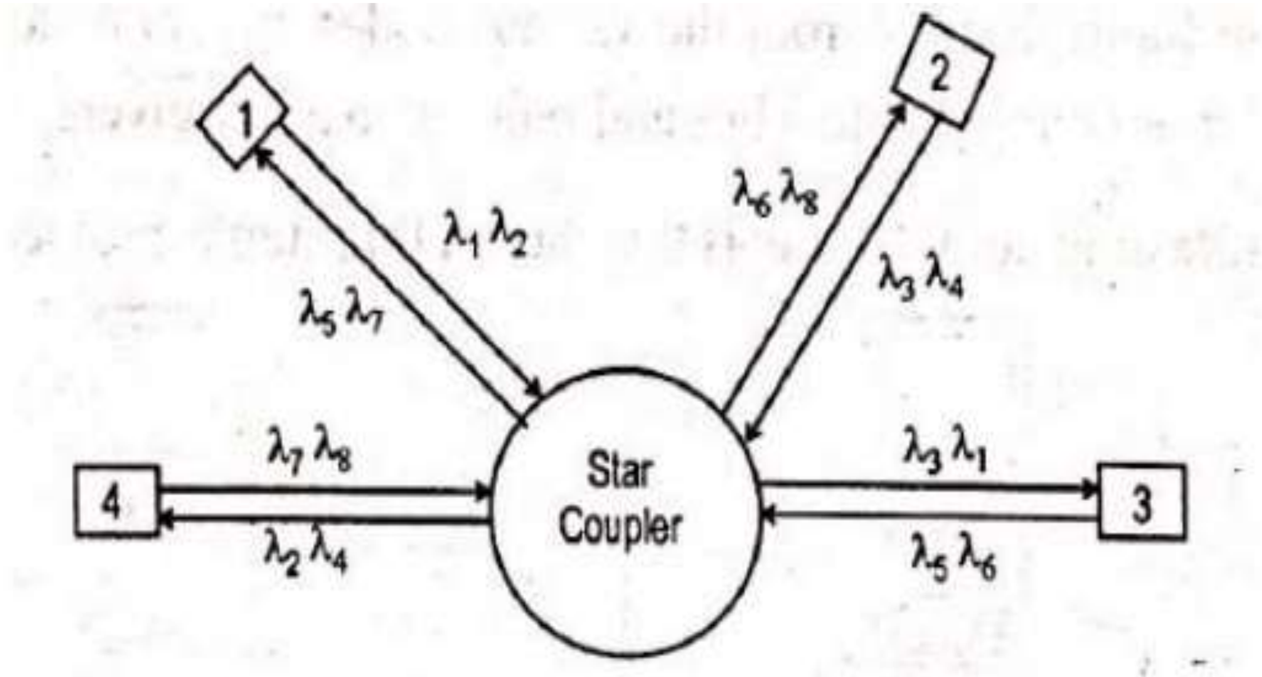


Figure 5.7 Broadcast and select Multihop networks

Drawback of single-hop networks is the need for rapidly unable lasers or receiver optical fibers.

- This drawback can be overcome by the designs of multi hop networks.
- Multihop networks do not have direct paths between each node pair.
- Each node has a small number of fixed tuned optical transmitter and receivers.

An example, a four node broadcast and select multi hop network where each node transmits on one set of two fixed wavelengths and receives on another set of two fixed wavelengths.

- Information destined for other nodes will have to be routed through intermediate stations.
- Considering the operation, a simplified transmission scheme in which message are sent as packets with a data field and an address header containing source and destination identifiers (i.e,. routing information) with control bits.

At intermediate node, the optical signal is converted to an electrical format.

- The address header is decoded to examine the routing information field, which will indicate where the packet should go.
- Routing information is used to send the electronic packets from optical transmitter to the next node in the logical path toward its final destination.
- **Advantage:** There are no destination conflicts or packet collisions in the network.
- For H hops between nodes, there is a network throughput penalty of at least 1/H.

The Shuffle Net Multihop Network

various topologies for multi hop light wave networks are

(1) The shuffle net graph

(2) The de Bruijin graph

(3) He toroidal Manhattan street network

- A scheme called the perfect shuffle is widely used to form processor interconnect patterns in multiprocessors.
- For optical networks, the logical configuration consists of a cylindrical arrangement of k column, each having p nodes. Where P is the number of fixed transceiver pairs per node.

The total number of nodes is then

$$N = kp^k \quad \text{... (5.18)}$$

where $k = 1, 2, 3, ...$

$p = 1, 2, 3, ...$

- The total number of wavelengths N_λ needed in the network is

$$N_\lambda = {}_pN = kp^{k+1} \quad \text{... (5.19)}$$

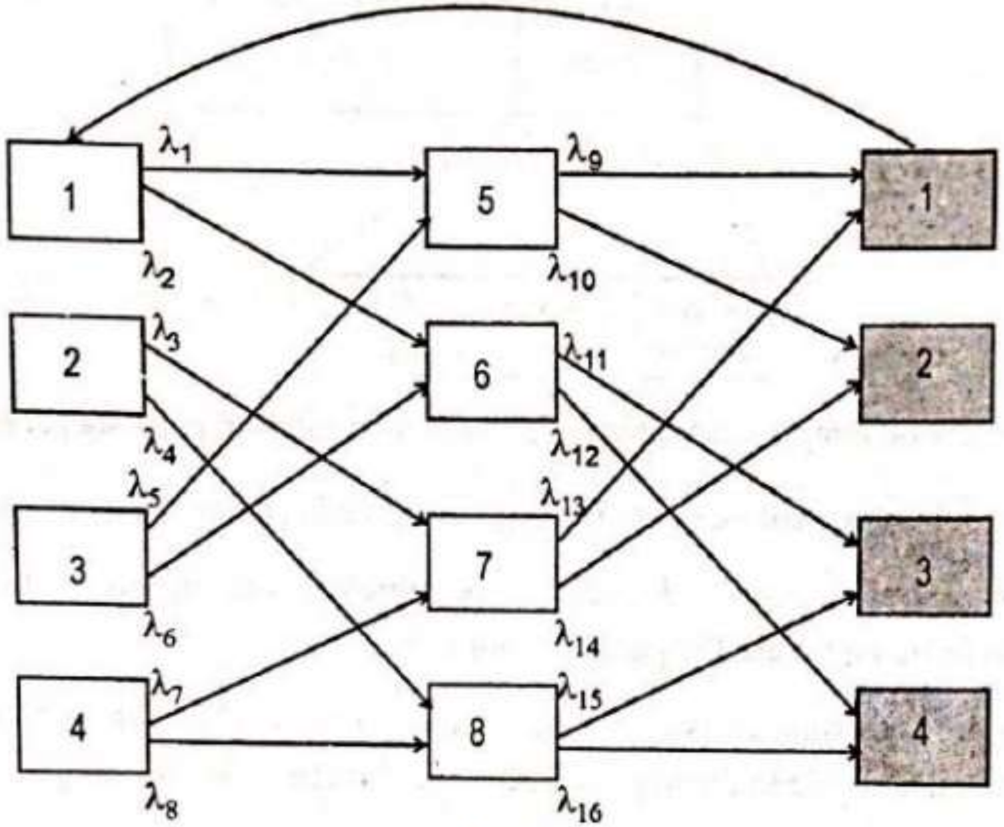


Figure 5.9 Shuffle Net

a (p,k)=(2,2) shuffle net, where the (k+1)th column represents the completion of a trip around the cylinder back to the first column.

- Performance parameter for the shuffle net is the average number of hops between any randomly chosen nodes.
- Since, all nodes have p output wavelength, p nodes can be reached from any node in one hop, p2 additional nodes can be reached in two hope, until all the (pk-1) other nodes are visited.
- The maximum number of hops is

$$H_{max} = 2k - 1 \qquad \text{...(5.20)}$$

Consider figure above, the connections between nodes 1 and 5 and nodes 1 and 7. In first case, the hop number is one.

- In second case three hops are needed with routes 1- 6 – 7 or 1 – 5 – 2 -7.?
- The average of hops Bar H of a shuffle net is

- The average number of hops $\overline{H}$ of a Shuffle Net is

$$\overline{H} = \frac{1}{N-1}\left[\sum_{j=1}^{k-1} j\,p^{j} + \sum_{j=0}^{k-1}(k+j)+(p^{k}-p^{j})\right]$$

$$= \frac{kp^{k}(p-1)(3k-1)-2k(p^{k}-1)}{2(p-1)(kp^{k}-1)} \qquad \text{...(5.21)}$$

In multi hopping, part of the capacity of a particular link directly connecting two nodes is actually utilized for carrying between them.

- The rest of the link capacity is used to forward messages from other nodes.
- The system has Np=kpK+1 links, the total network capacity C is

$$C = \frac{kp^{k+1}}{\overline{\overline{H}}} \qquad \dots (5.22)$$

The per-user throughput δ is

$$\delta = \frac{C}{N} = \frac{P}{\overline{\overline{H}}} \qquad \dots (5.23)$$

Different (p,k) combination result in different throughputs, to get a better network performance.

-

Wavelength Routed Networks

Two problems arise in broadcast and select networks,

- More wavelengths are needs as the number of nodes in the network grows.
- Without the widespread are use of optical booster amplifier, due to this splitting losses is high.

- Wavelength routed networks overcome these limitations through wavelength reuse, wavelength conversion, and optical switching.
- The physical topology of a wavelength routed network consists of optical wavelength routers interconnected by pair of point-to-point fiber link in an arbitrary mesh configuration.

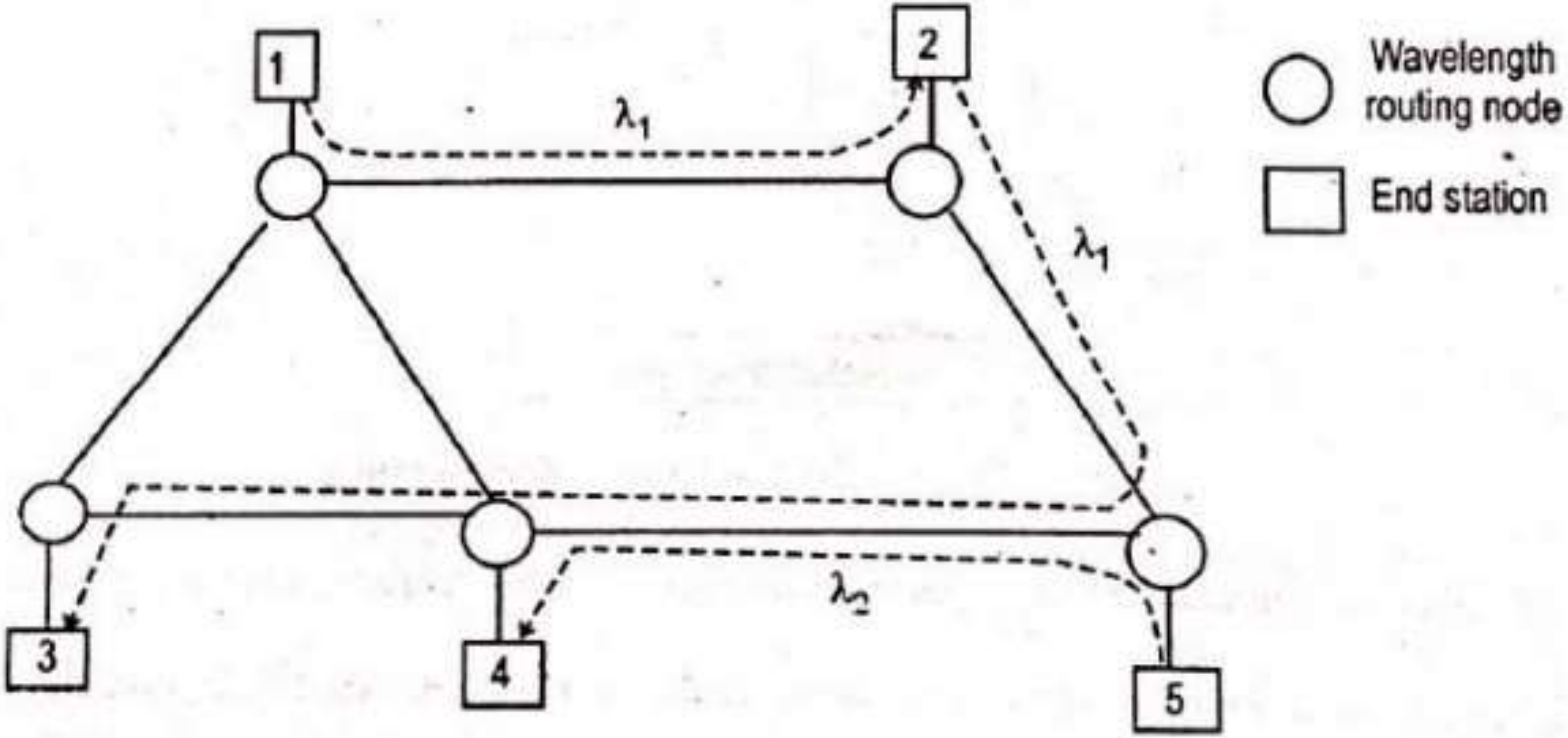


Figure 5.10 Wavelength Reuse on Mesh Network

Each link can carry a certain number off wavelength which can be directed independently to differently output paths at a node.

- Each node may have logical connections with several other nodes in the network, where each connection uses a particular wavelength.
- The paths taken by any two connections do not overlap, they can use the same wavelength.

Optical CDMA

The simplest configuration , CDMA achieves multiple access by assigning a unique code to each user.

- To communicate with another node, user imprint their agreed upon code onto the data. The receiver can then decode the bit stream by locking onto the code sequence.
- The principle of optical CDMA is based on spread-spectrum techniques.
- The concept is to spread the energy of the optical signal over a frequency band that is much wider than the minimum bandwidth required to send the information.

- Spreading is done by a code that is independent of the signal itself.
- On optical encoder is used to map each bit of information into the high-rate (longer-code-length) optical sequence. The symbols is the spreading code are called chips.
- The energy density of the transmitted waveform is distributed more or less uniformly over the entire spread-spectrum bandwidth.
- The set of optical sequences becomes a set of unique ‘address codes or signature sequences’ the individual network users.

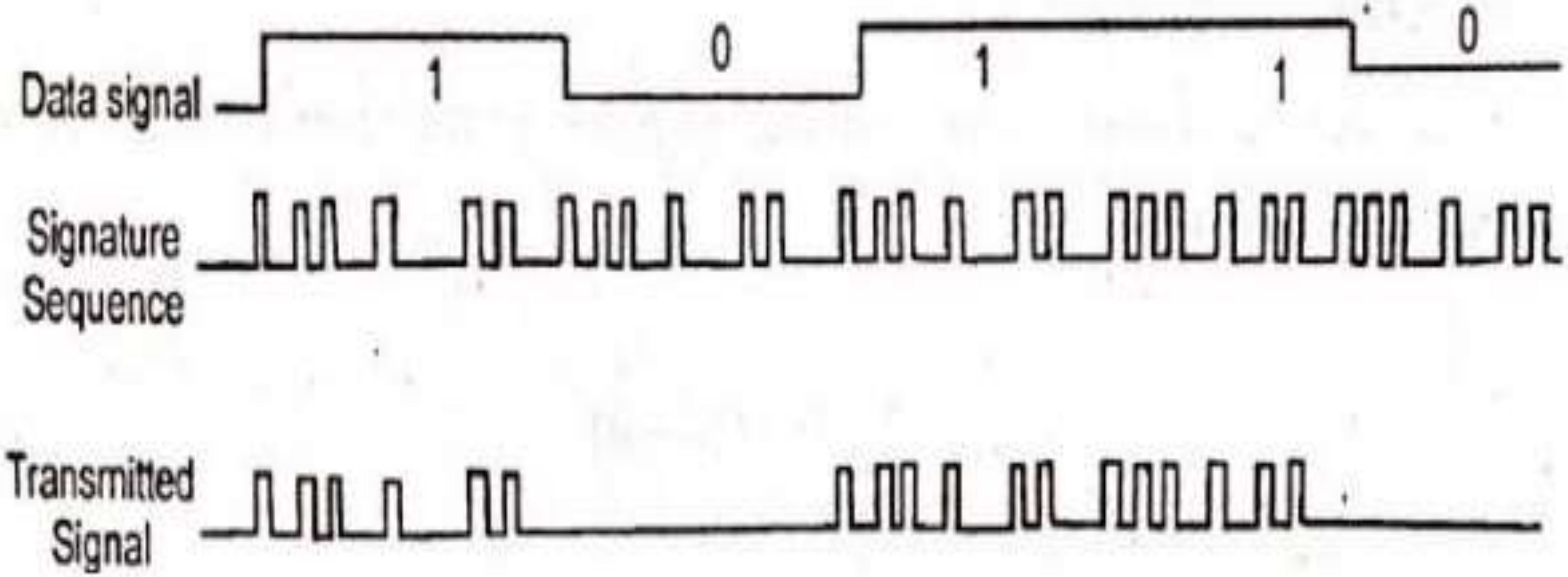


Figure 5.20 Six Chip optical CDMA Encoding Scheme

- The signature sequence contains six chips. When the data signal contains 1 data bit, the six-chip sequence is transmitted, no chips are sent for a 0 data bit.
- Time-domain optical CDMA allows a number of users to access a network simultaneously, through the use of a common wavelength.

- Both asynchronous and synchronous optical CDMA techniques. In synchronous accessing schemes follow rigorous transmission schedules, the produce more successful transmission (higher throughputs) than asynchronous methods where network access is random and collisions between users can occurs.
- An optical CDMA network is based on the use of a coded sequence of pulses.
- The setup consists of N transmitter and receiver pairs interconnected in a star

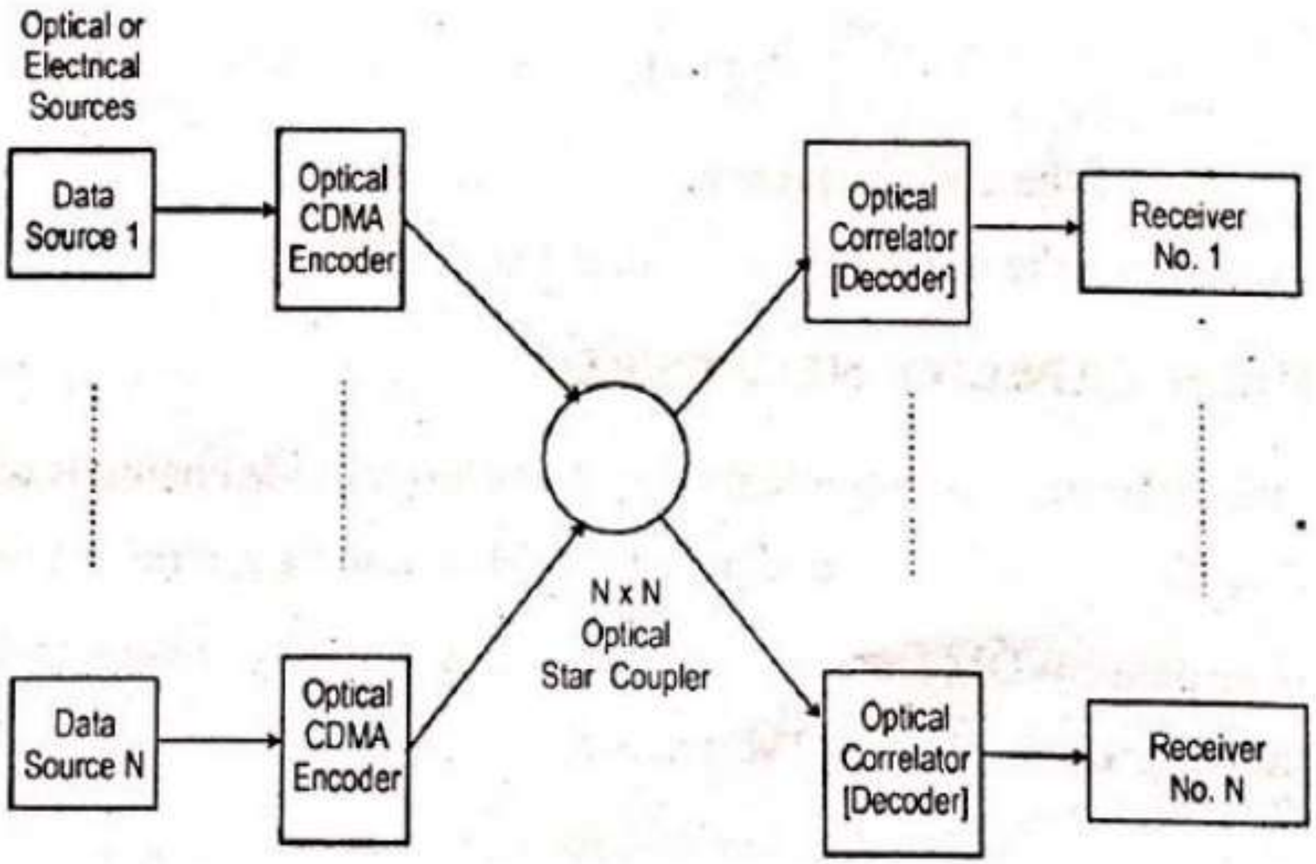
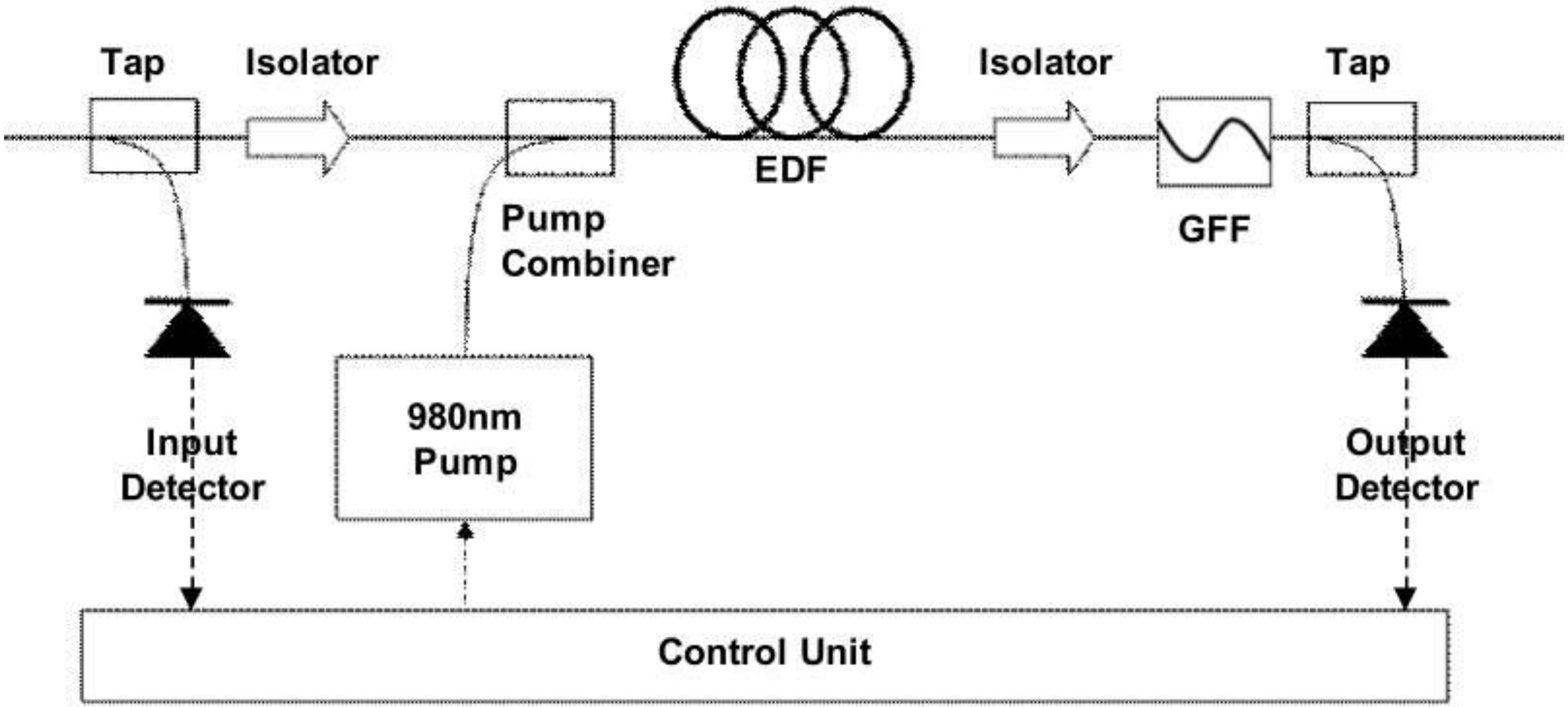


Figure 5.21 Optical CDMA Network Based on Using a Coded Sequence Pulse

Basics of EDFA

The key feature of EDFA technology is the Erbium Doped Fiber (EDF), which is a conventional silica fiber doped with erbium. Basically, EDFA consists of a length of EDF, a pump laser, and a WDM combiner. The WDM combiner is for combining the signal and pump wavelength so that they can propagate simultaneously through the EDF. EDFAs can be designed that pump energy propagates in the same direction as the signal (forward pumping), the opposite direction to the signal (backward pumping), or both direction together. The pump energy may either by 980nm pump energy or 1480nm pump energy, or a combination of both. The most common configuration is the forward pumping configuration using 980nm pump energy. Because this configuration takes advantage of the 980nm semiconductor pump laser diodes, which feature effective cost, reliability and low power consumption. Thus providing the best overall design in regard to performance and cost trade-offs.

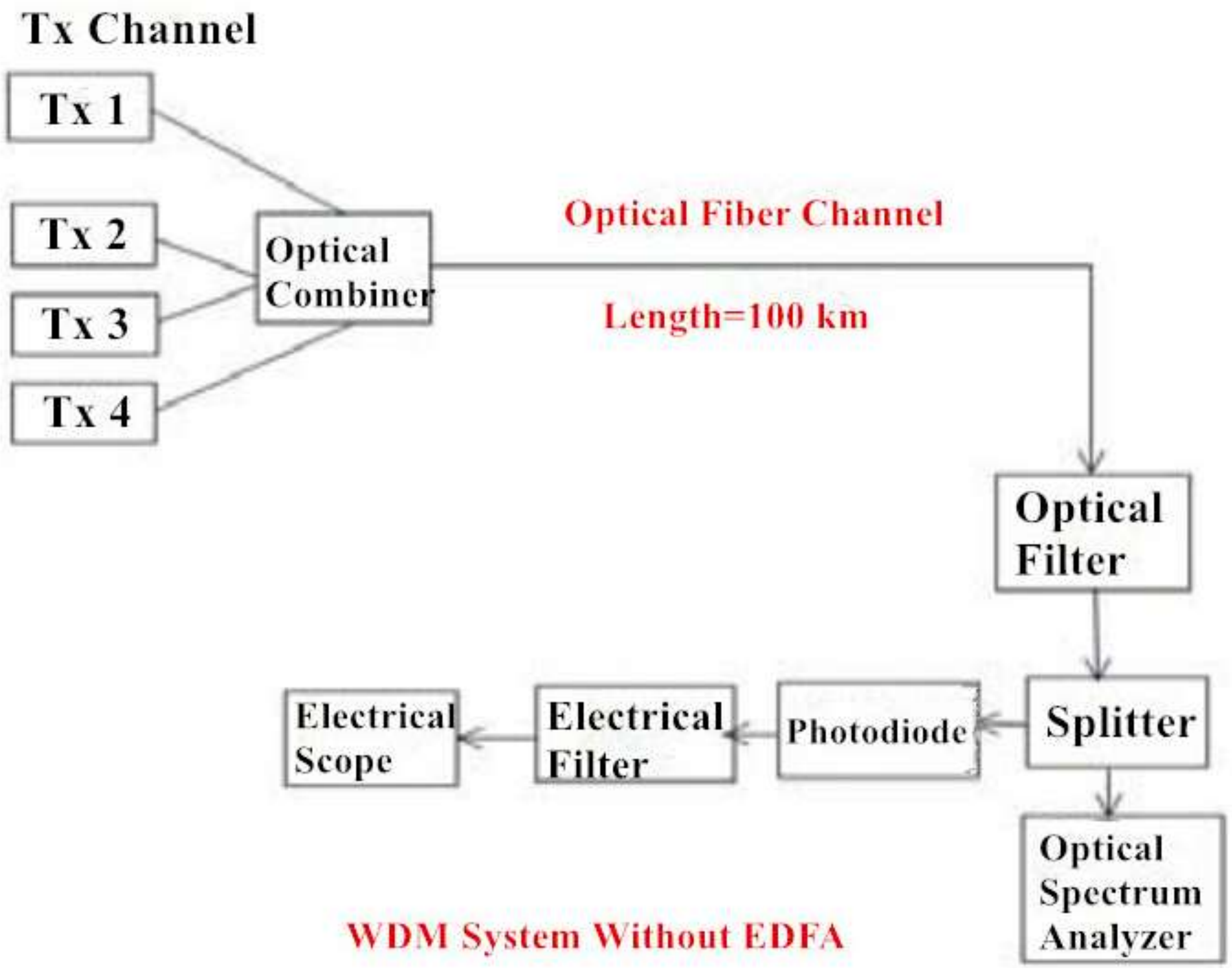

Tap
Isolator
EDF
Isolator
Tap
Pump
Combiner
GFF
980nm
Pump
Input
Detector
Output
Detector
Control Unit

Why EDFA Is Essential to WDM Systems?

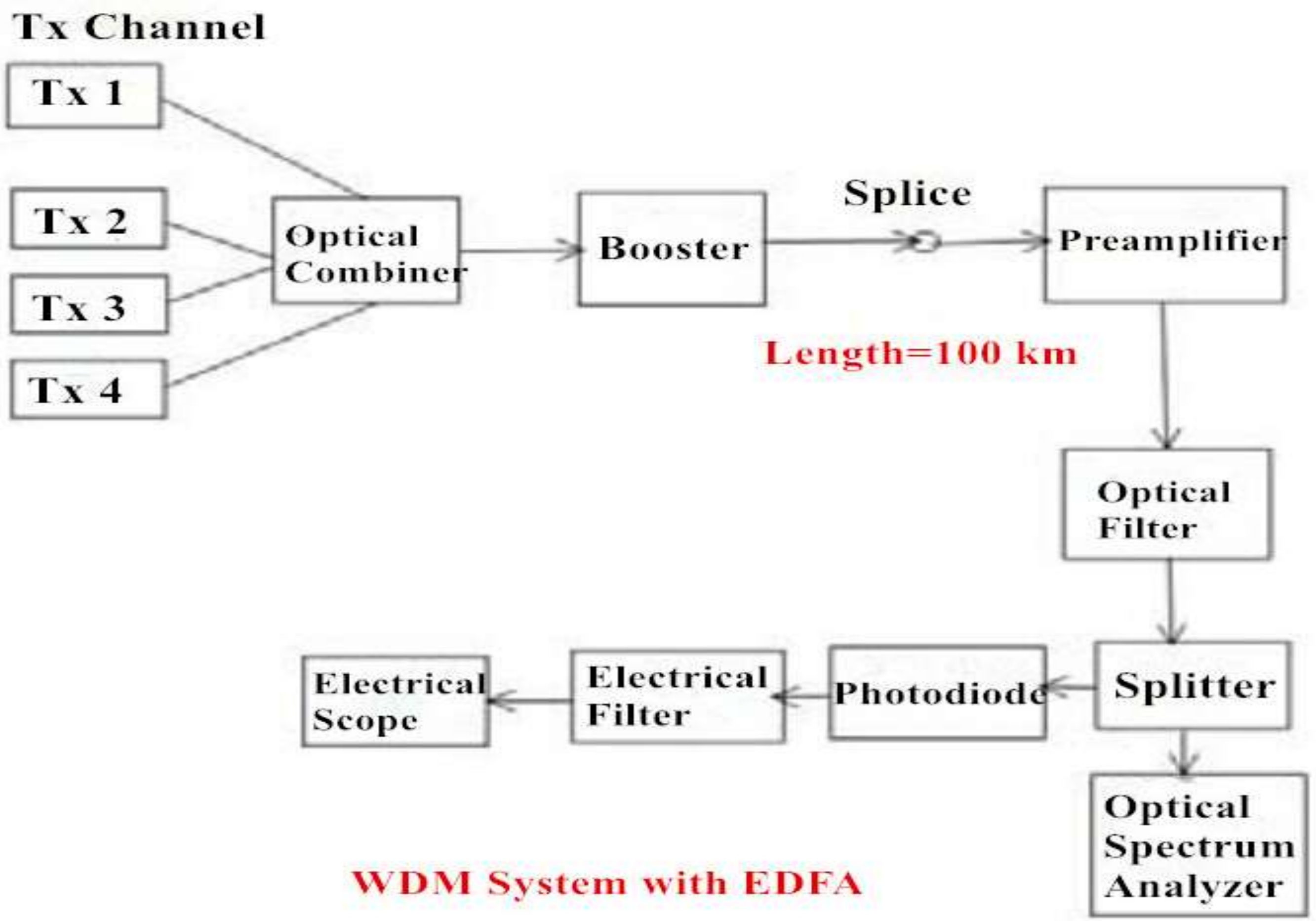
We know that when transmitting over a long distance, the signal is highly attenuated. Therefore it is essential to implement an optical signal amplification to restore the optical power budget. This is what EDFA commonly used for: it is designed to directly amplify an input optical signal, which hence eliminates the need to first transform it to an electronic signal. It simply can amplify all WDM channels together. Nowadays, EDFA rises as a preferable option for signal amplification method for WDM systems, owing to its low-noise and insensitive to signal polarization. Besides, EDFA deployment is relatively easier to realize compared with other signal amplification methods.

Channel WDM System With or Without EDFA: What Is the Difference?

Two basic configurations of WDM systems come in two forms: WDM system with or without EDFA. Let's first see the configuration of a WDM system without using it. At the transmitter end, channels are combined in an optical combiner. And these combined multiple channels are transmitted over a single fiber. Then splitters are used to split the signal into two parts, one passes through the optical spectrum analyzer for signal's analysis. And other passes through the photodetector to convert the optical signal into electrical. Then filter and electrical scope are used to observe the characteristics of a signal. In this configuration signals at a long distance get attenuated. While this problem can be overcome by using erbium-doped fiber amplifier.


Tx Channel
Tx 1
Tx 2
Tx 3
Tx 4
Optical Combiner
Optical Fiber Channel
Length=100 km
Optical Filter
Splitter
Photodiode
Electrical Filter
Electrical Scope
Optical Spectrum Analyzer
WDM System Without EDFA

As for WDM system which uses EDFA, things are a little bit different. Although the configuration is almost the same as a WDM system without it, some additional components are used. These components are EDFAs which are used as a booster and pre-amplifier, and another additional component is an optical filter. With the adoption of an optical amplifier, this system doesn't suffer from losses and attenuation. Hence, it is possible to build broadband WDM EDFAs which offer flat gain over a large dynamic gain range, low noise, high saturation output power and stable operation with excellent transient suppression. The combination provides reliable performance and relatively low cost, which makes EDFAs preferable in most applications of modern optical networks.



WDM System with EDFA

Among the various technologies available for optical amplifiers, EDFA technology proves to be the most advanced one that holds the dominant position in the market. In the future, the WDM system integrated with high-performance EDFA, as well as the demand for more bandwidth at lower costs have made optical networking an attractive solution for advanced networks.

Performance of WDM+EFDA

An optical network that involves WDM (wavelength division multiplexing) currently gains in much popularity in existing telecom infrastructure. Which is expected to play a significant role in next-generation networks to support various services with a very different requirement. WDM technology, together with EDFA (Erbium Doped Fiber Amplifier), allowing the transmission of multiple channels over the same fiber, that makes it possible to transmit many terabits of data over distances from a few hundred kilometers to transoceanic distances, which satisfy the data capacity required for current and future communication networks. This article explains how can WDM system benefit from this technology.

- To send information from node j to node k, the address code for node k is impressed upon the data by the encoder at node j.
- At the destination, the receiver differentiates between codes by means of correlation detection.
- Each receiver correlates its own address f(n) with the received signal s(n). The receiver output r(n) is

$$r(n) = \sum_{k=1}^{N} s(k)\, f(k-n) \qquad \ldots(5.57)$$

If the received signal arrives at the correct destination, then s(n)=f(n).

Equation (5.57) represents an autocorrelation function, if s(n) not equal to f(n) the equation (5.57) represents a cross-correlation function.

For a receiver to be able to distinguish the proper address correctly, it is necessary to maximize the autocorrelation function and minimize the cross-correlation function.

Prime-sequence codes and optical orthogonal codes (OOCs) are the commonly used spreading sequences in optical CDMA systems.

An OOC systems the number of simultaneous user an is bounded by

$$N \leq \left\lfloor \frac{F-1}{K(K-1)} \right\rfloor \quad \text{... (5.58)}$$

ULTRA HIGH CAPACITY NETWORKS

Advance of optical communication systems has provide channels with enormous bandwidth at least 25THz and dense WDM technology, ultrafast optical TDM.

To using dense WDM techniques to increase the capacity of long-haul transmission link and ultrafast optical TDM schemes.

These are particularly attractive in LAN or MANs

TDM Schemes To Shared-Media Local Neteorks Have Two Methods:

(1) Bit-interleaved TDM.

(2) Time-slotted TDM.

1. Ultra High Capacity WDM Networks

Two popular approaches are used to achieve increased capacity.

(a) to widen the spectral bandwidth of EDFAs from 30 to 80 nm, by using broadening techniques.

(b) Increasing the capacity of a WDM link is to improve the spectral efficiency of the WDM signals.

Most of the demonstrations use a rate of 20 Gb/s for each individual wavelength to avoid non-linear effects.

Examples are,

(1) A 50-channel WDM system operating at an aggregated 1-Tb/s rate over a 600 km link.

(2) A 132-channel WDM system operating at an aggregated 2.6 Tb/s rate over a 120-km/link.

2. Bit-Interleaved Optical TDM

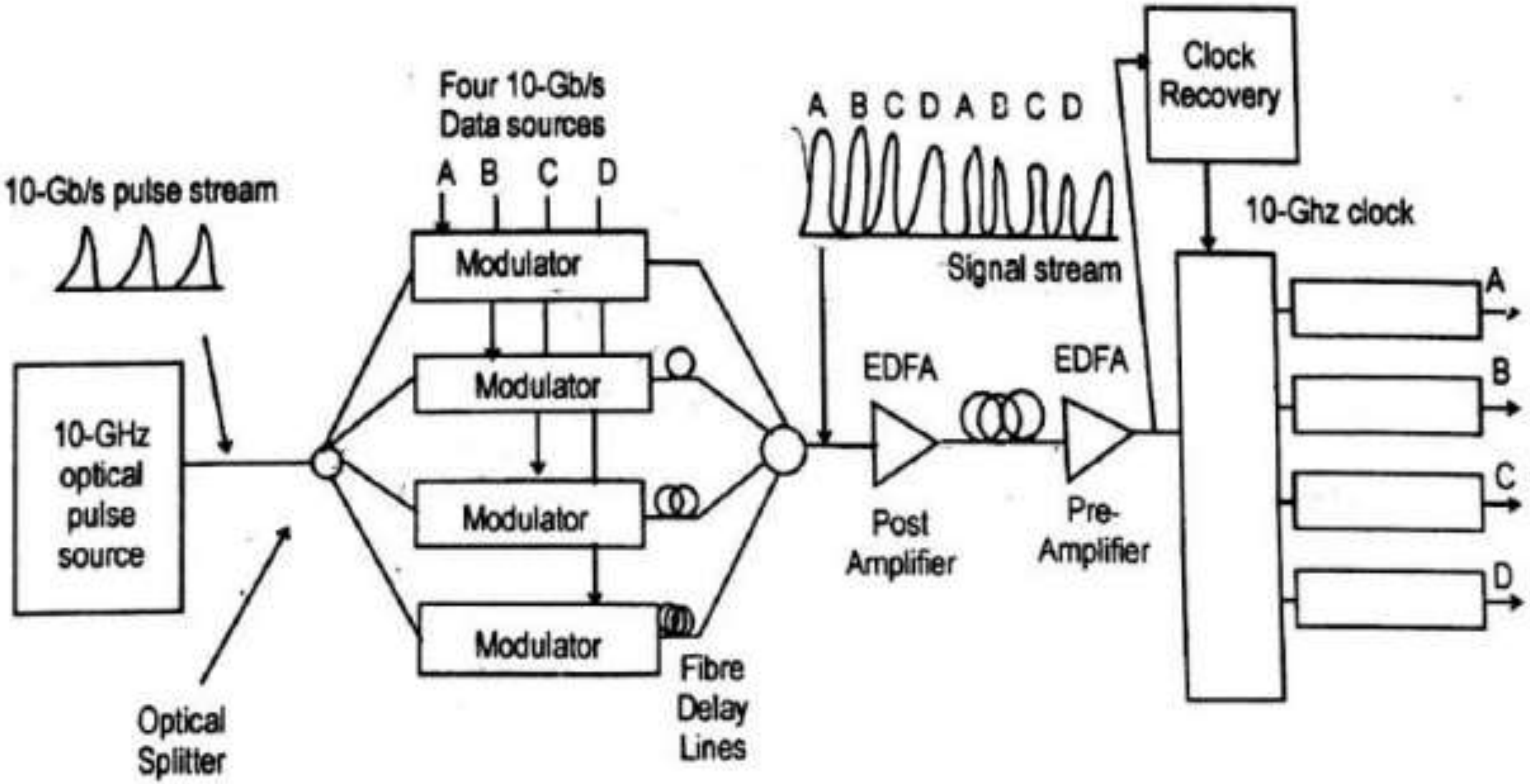


Figure 5.22 Ultrafast Point – Point Transmission System Using Optical TDM

- Repetition rate typically ranges from 2.5 to 10 Gb/S, which corresponds to the bit rate of the electric data tributaries feeding the system.
- An optical splitter divides the pulse train into N separate streams.
- The pulse streams is 10 Gb/S and N=4, each of these channels is then individually modulated by an electrical tributary data source at a bit rate B.
- The modulated outputs are delayed individually by different fractions of the clock period, and are then interleaved through an optical combiner to produce an aggregate bitrate of NXB.
- Optical post amplifier and preamplifier are generally included in the link to compenstate for splitting and attenuation loss.
- At the receiving end, the aggregate pulse stream is demultiplexed into the original N independent data channels for further signal processing.
- A clock-recovery mechanism operating at the base bit rate B is required at the receiver to drive and synchronize the demultiplexer.

Thank You!